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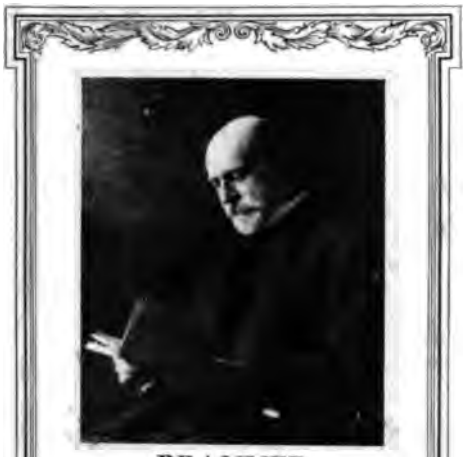
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VOLUME 2

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THE

GEOLOGY OF POINT SAL.

BY

HAROLD W. FAIRBANKS

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INTRODUCTION.*

Point Sal is situated in the extreme northwestern portion of Santa Barbara County. It forms the termination of a low range of hills about midway between Point Arguello and Port Harford. North and south there are many miles of continuous sandy beaches. Although Point Sal does not form a very marked break in the regularity of the coast line, yet it shows several miles of rocky cliffs which offer exceptional exposures for the study of its remarkably interesting geology.

The geographical features of the accompanying map have been taken from the map of Santa Barbara County, the contours having been added with the aid of an aneroid. The area included comprises all that portion of the region about Point Sal which presents any marked geological interest. It is five and a half miles from north to south and four and a half from east to west, containing about sixteen square miles.

As Point Sal lies away from the main lines of travel, none of the parties of the earlier geological surveys ever visited the section, and no references to its geology have been published except a brief notice by the author.†

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*The author is indebted to Mr. C. H. Clark, of Point Sal, and to Mr. P. H. Dallidet, Jr., of San Luis Obispo, for kindnesses shown during the field work.

†XII Report of the State Mineralogist of California, p. 506.

TOPOGRAPHY.

The line of hills terminating in Point Sal is bordered on the north by the broad valley of the Santa Maria River, and on the south by the Jesus Maria River and the Los Alamos Valley. It extends southeasterly as a low swell of land, finally joining with the San Rafael Mountains in the central part of Santa Barbara County.

That portion of the ridge distinctly belonging to Point Sal is cut off by a low pass, called Shuman Cañon, about ten miles from its northwestern extremity. On the southern side of the pass heads the Casmalia, a small stream which flows west into the ocean.

Viewed from the north, in the Santa Maria Valley, the ridge terminating in Point Sal appears as a long, even elevation. Upon closer examination a cañon of considerable length is seen to head on the northern slope. It forms the dividing line between two strongly marked topographies. On the northwest, extending to the ocean cliffs, and to the summit of the ridge, is a gently undulating slope rising gradually from the valley of the Santa Maria. On the southeast, the higher and more deeply eroded hills rise very abruptly from the valley. Viewed from the southern side, a much more complicated topography appears. The western extremity of the ridge, terminating in Point Sal proper, in marked contrast to the gradual rise of its northern slope, descends very precipitously to the ocean from an altitude of 1,000 feet. The average slope from the summit to the ocean is 25 degrees, reaching in some places nearly 35 degrees. From the Old Landing southeasterly the slope becomes more gradual. The main portion of the ridge, southeast of the point where the road crosses it, is remarkably even and regular. The main elevation is seen to be divided into a number of parallel ridges, separated more or less by longitudinal valleys. Toward the southwest the main ridge presents a regular front, circling somewhat amphitheater-like, in which head a number of streams flowing in a uniformly southwest direction. The great regularity of the summit of this portion of the ridge, which reaches an elevation of 1,500 feet, and the amphitheater-like basin on the southwest, are most striking features in the topography. The regularity is due in part at least to the fact that the strata on the summit are nearly flat, and

composed of the resistant Miocene flints, while on the southern slope the bituminous shales are followed in descending order by a great thickness of gypsiferous clays, in which broad valleys have been eroded. Lower down toward the ocean the clays are replaced by strata of volcanic ash, sandstone, and conglomerate, in which, because of their greater resistance, cañons have been eroded. The strata of volcanic ash form very striking features in the landscape on the lower slopes of the ridge; being interbedded with soft clays, they weather out in cliffs and projecting ridges. The streams cross a terrace, on emerging from the hills, which widens toward the southeast. They have cut through the soil, and in the case of the softer rocks have eroded their channels so that they enter the ocean at a uniform grade, but where they cut across the gabbro and serpentine, a fall occurs on the ocean cliff. The cañons of these streams give excellent sections of the strata from the ocean to the summit of the ridge.

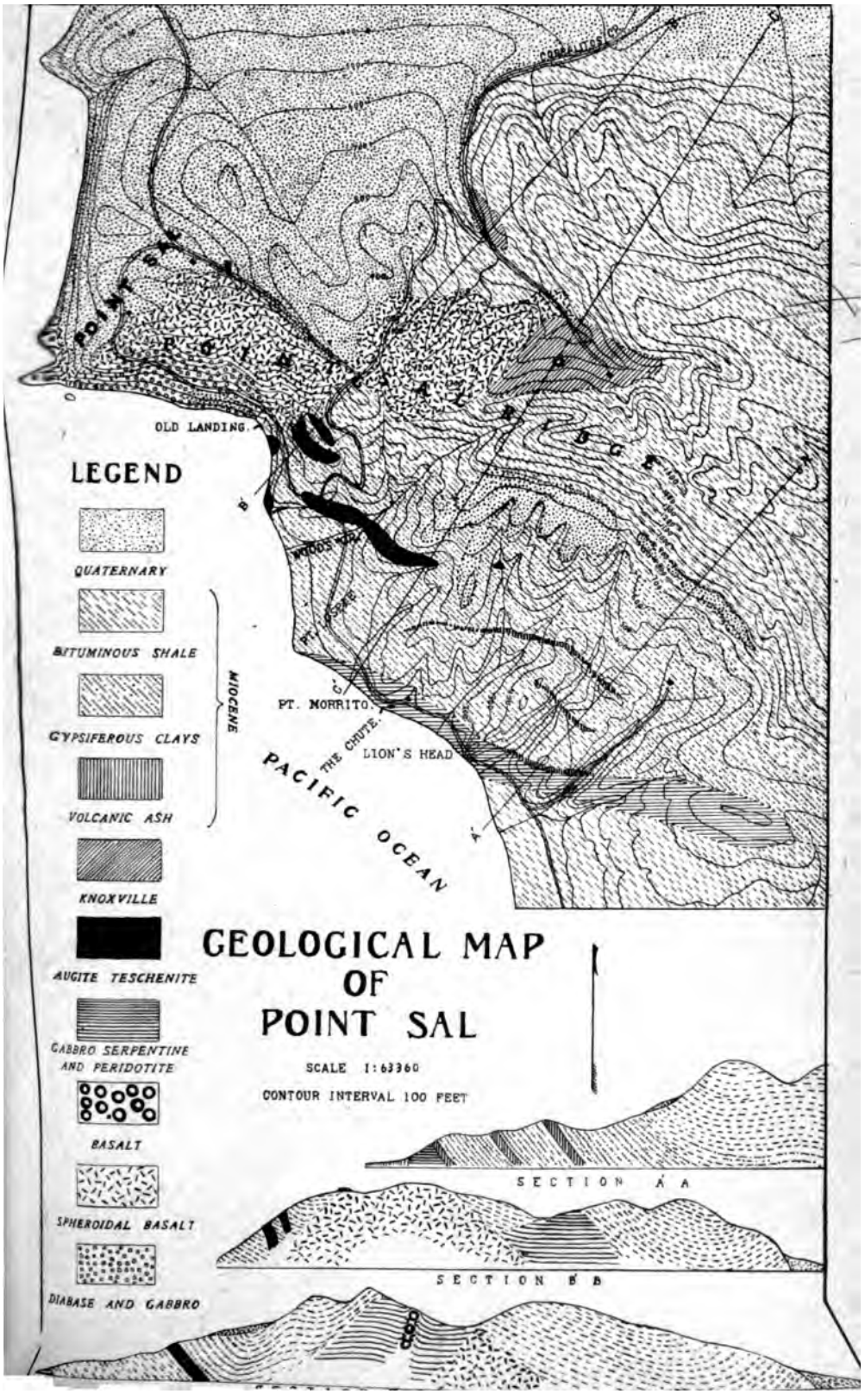
The designation Lion's Head has been given to a picturesque and precipitous mass of serpentine which rises very abruptly from the water to a hight of 400 feet.

OUTLINE OF THE GEOLOGY.

Except for the area which forms the subject of this paper, the line of hills terminating in Point Sal consists, as far as is known, of Miocene and more recent strata. The region about the Point itself has, however, been the scene of many violent disturbances and repeated eruptions of basic magmas. A part of these consolidated as surface flows, while others have the characters of deep-seated rocks.

The sedimentary strata comprise only the Pleistocene, Miocene, and Knoxville. The Pleistocene forms a rim about the southern slope of the ridge, the greater portion originally existing on this side having been removed by erosion. On the northern slope it forms a continuous sheet from the valley to the summit between the ocean and Corralitos Creek.

The Miocene is the most extensive formation represented. It covers the greater part of the northern and eastern portions of the area mapped. It is divisible into two distinct parts: the upper, the


POINT SAL
POINT SAL RIDGE
OLD LANDING
LEGEND
QUATERNARY
BITUMINOUS SHALE
GYPSIFEROUS CLAYS
VOLCANIC ASH
MIOCENE
KNOXVILLE
AUGITE TESCHENITE
GABBRO SERPENTINE AND PERIDOTITE
BASALT
SPHEROIDAL BASALT
DIABASE AND GABBRO
PT. MORRITO
THE CHUTE
LION'S HEAD
PACIFIC OCEAN
GEOLOGICAL MAP OF POINT SAL
SCALE 1:63360
CONTOUR INTERVAL 100 FEET
SECTION A A'
SECTION B B'

bituminous shales, and the lower, the gypsiferous clays. Below the clays are sandstone, shales, and conglomerates resting on the gabbro and serpentine.

The bituminous shales form the most of the higher portions of the ridge. They also appear on the coast in the northeast corner of the map, and in the southern part constituting the coast line south of the serpentine. In the two latter occurrences they are richly impregnated with bituminous matter. The strata of volcanic ash appear in the lower Miocene beds. There are three distinct horizons, the lowest resting on the gabbro.

The Knoxville is represented by two areas in the valley of Corralitos Creek. The upper one is much the more extensive, forming almost the whole of the head of the valley. These are the first recognized beds of lower Cretaceous age in Santa Barbara County, and the most southern point at which the genus Aucella has been discovered in California.

The eruptive rocks, though presenting great variations, are, with the exception of some unimportant facies, very basic. They range in age from a period probably antedating the Knoxville to post-Miocene. The youngest eruptive body has a character very similar to the analcite diabase, previously described by the author, from San Luis Obispo County, California.* Carefully conducted investigations upon the material from Point Sal have, it seems to the author, conclusively demonstrated that this eruptive should be classed with the group of rocks known as the teschenites, and that this group, although its individuality is in dispute among European petrographers, has a real existence as a distinct type. The different occurrences of this rock at Point Sal all possess a diabasic structure, appearing in the form of dikes in the Miocene.

The eruptive which seems to be the next in age is that of which the gabbro and peridotite are differentiated products. It extends easterly from Point Lospie for three miles in the form of a long, narrow dike. For two miles there are clean-cut exposures in the ocean cliffs, and then it passes inland, terminating about a mile from the sea, in a rounded hill rising to a hight of 700 feet. The

*Bull. Dept. Geol., Univ. Cal., pp. 273–300.

exposures in the ocean cliffs show this eruptive mass to be an exceedingly complicated one. While it is divided in a general way into two parts, the one chiefly peridotite, the other gabbro, yet the irregular junction between the two and the latter dikes of diabase, norite, gabbro and intermediate types all together constitute a complex whose history would be impossible of elucidation were it not for the clean surfaces afforded by the action of the waves.

Probably the oldest eruptive complex is that formed of the spheroidal basalt, diabase and gabbro. The spheroidal basalt forms the surface of the ridge for a distance of nearly three miles, extending from the head of Corralitos Creek continuously northwest to the end of Point Sal. The peculiar spheroidal character is developed mainly at the extreme end of the Point. On the steep southern slope of the Point the basalt is followed downwards first by dikes and then by a massive body of diabase, which in turn finally gives place to gabbro along the ocean cliffs. The relation existing between these different bodies of rock is quite complex. While all evidently constitute a geological unit, different periods of eruption and intrusion are clearly shown. The upwelling body of diabase and gabbro has broken through the banded lavas and have in turn been cut by later dikes of the same character. At one spot appears what is evidently a volcanic chimney filled with an agglomerated breccia of dark aphanitic lava mingled with flows of the same material. The age of these rocks is not definitely known, but for reasons which will be given later they are believed to antedate the Knoxville.

The smallest eruptive body present is one somewhat laccolitic in character, which has been forced up into the Knoxville shales.

PLEISTOCENE.

Extent and Character.—The largest area of Pleistocene is that lying west of Corralitos Creek and north of the summit of the ridge. Its surface is sandy and barren, its topographic features being in most marked contrast to those of the other formations. The strata consist chiefly of indistinctly stratified sand, which shows but a slight degree of consolidation. These beds are seen to the best advantage in a cañon emptying into the ocean a mile and a half north of Point Sal, where a thickness of about three hundred feet

is exposed. The strata are perfectly horizontal and seem to have been lifted without any disturbance. A remnant of these beds of similar character and horizontally bedded occurs on the summit of the ridge where the road crosses, the altitude being 1,050 feet. This outcrop almost overlooks the steep descent to the Old Landing. Fragments of shells are scattered in many places over the surface of this formation up to an elevation of 900 feet. The following species were determined: *Pupura canaliculata*, Ducl.; *Chlorostoma*

FIGURE 1.—Pleistocene mesa on the southern side of the Point Sal Ridge.

brunneum, Phil.; *Mytilus californicus*, Con.; *Lunatia Lewisii*, Gld.; *Haliotis*, sp. These species are all living. Remnants of a gently sloping Pleistocene mesa also occur on the south side of the ridge. These are particularly noticeable about the heads of the valleys which have been eroded in the gypsiferous clays, and on the ridges between the small streams which head above the clays.

At the head of the valley north of the dairy the rim of Pleistocene is very narrow, and consists chiefly of fragments from the bituminous shales above. Springs impregnated with calcium carbonate have thoroughly cemented the fragmental mass and formed beauti-

ful hollow casts of a number of species of shells. The most of them could not be determined, although *Crepidula rugosa*, Nutt., and a *Pupura* were recognized. The Pleistocene mesa is broadest a little east of Wood's Creek, where it is undergoing the peculiar "bad land" erosion often seen in strata of this age along the coast (Fig. 1). It is very similar to the Pleistocene capping of Point Loma, in the southern part of the state, even to the presence on the surface of small concretionary nodules formed of sand cemented by iron oxide. The mesa forms an even encircling rim about the Miocene hills at an elevation of 950 to 1,000 feet, and extends down the transverse ridge east of Wood's Creek to an elevation of 500 feet.

It would appear that this post-Pleistocene elevation is probably identical with that noted at other points along the coast.

On the south side of the Point Sal ridge, between the Old Landing and the Point, is a narrow strip of land, sufficiently flat to be cultivated, and known locally as the Mesa. Its upper edge has an elevation of a little over three hundred feet. It is composed of stratified sand and fragments from the steep mountain above. Whether it can be correlated with the Pleistocene just described is not certain.

Elevated Beaches.—The records of at least four different ocean levels besides the present were recognized on Point Sal, the highest being that of the Pleistocene mesa, reaching an elevation of 1,050 feet. The next one has an elevation of only about 115 feet, and was distinguished along the banks of the first creek emptying into the ocean east of the Chute. It consists of a bed of washed gabbro boulders. What is probably the same shore line is rather indistinctly shown on the seaward face of the Lion's Head. It would be very pronounced if it were not for the crumbling of the cliff above. The two lower terraces are most distinctly marked in the diabase cliff west of the Old Landing. The narrow mesa before referred to, overlies them at one point, and it is due to this fact that they are so finely preserved. The lower one has an elevation of 25 feet, the upper of 80. Both form well-marked benches in the diabase, with washed boulders at their upper limits, above which the cliff in each case rises almost vertically. The stratified sands and gravel of the

mesa terrace rest directly on these benches, showing them to be older. Although the upper part of this mesa appears to be a detrital slope, the lower has more the appearance of a submarine deposit.

MIOCENE.

Bituminous Shales.—The bituminous shales form the upper horizon of the Miocene within the area mapped, being quite sharply defined from the gypsiferous clays below. There is a small exposure of these rocks on the little point about a mile and a half north of Point Sal. Here they consist of flinty strata, dark shales, and limestone richly impregnated with bituminous matter. They have suffered much disturbance, and are contorted in a marked degree. At one spot a syncline perhaps 25 feet across has been cut away in such a manner as to leave a natural arch, the faces of which correspond to the stratification.

In the southern portion of the map there is an arm of the bituminous shales, occupying a position between the serpentine and the ocean. They are well exposed at the mouth of the cañon below the dairy, where they rest on or against the serpentine. They have undergone compression and are greatly contorted. The basal portion of the series is composed chiefly of clear, flinty rocks, showing abundant remains of organisms visible to the unaided eye. The flints are very regularly banded, those of clear opaline appearance alternating with bands of a duller color and less silicious composition, in an exposed thickness of about 100 feet.

The contact with the serpentine is not visible in the cliffs on the coast. It is probable that extensive faulting has taken place along the peridotite-gabbro axis, for the nearest exposures of the shale have a vertical dip, while the adjoining serpentine is greatly crushed. The dip of the shales gradually becomes less to the south away from the serpentine. They can be traced for about 2,000 feet, and then disappear beneath the Pleistocene sands. Nowhere in the rocks of this series has the author observed any more regularly fissile and banded structures. The total thickness represented here can not be less than 1,000 feet. No fossils were found except *Pecten peckhami*, Gabb, which seems to be confined to rocks of this char-

acter. The strata are highly bituminous, more especially the limestone. The latter appears to be formed almost exclusively of minute organisms.

The bituminous shales form all of the higher part of the ridge lying east of the spheroidal basalt. The structure of the main ridge facing the south is that of a flat syncline. Toward the north the strata are nearly flat for some distance, so that the banded flints forming the summit on the south are repeated on the tops of the several nearly parallel interlocking ridges. Passing up the main gulch, which heads on the south side of the highest part of the ridge, the gypsiferous clays are seen to be replaced by a yellow earthy variety of the shales. Farther up the hills the strata become harder and lighter colored until they terminate in the flints at the top. Specimens of *Pecten peckhami*, Gabb, were found toward the upper part of the series. The hills lying between the head of Corralitos Creek and the Santa Maria Valley diverge somewhat from the main ridge. They belong to the bituminous shale series, but are more earthy than that on the south. They dip away from the Knoxville and the basaltic ridge, and on the northern slope of the hills present a bold front to the valley. On that side they dip into the ridge, that is to the south, thus forming a syncline.

Petrography.—These rocks present very diverse characters. They vary from those which are almost pure limestone through calcareous sandstones and clayey marly rocks to the yellowish white porcelain-like rocks and clear opaline flints. The latter form the upper portion of the great thickness of Miocene strata. They have the same character as in other portions of the Coast Ranges. They are generally well banded, the bands sinking to microscopic proportions and often exhibiting a wavy character which may be primary. They vary in color from the light clear opaline variety, through brown with a resinous luster to those which are jet black. They have been affected to a limited extent by a secondary action resulting in the deposition of chalcedonic silica in the cracks and cavities. When examined with the hand lens much of this rock is seen to be thickly specked with little round dots, averaging, perhaps, a millimeter in diameter. A specimen of the black flints thus marked was chosen for a slide but was found exceedingly difficult to cut. Under

the microscope it appeared to consist of an aggregate of minute and strongly polarizing grains of chalcedonic quartz. The circular areas did not appear as numerous as in the hand specimen, and were only faintly distinguished by clearer polarization. Numerous specimens were observed in which there was a confused mixing of the clear flint with that of a dull color. These two kinds were related in such a manner as to preclude the idea that it was due to any original difference but was suggestive of secondary change. The clear portions seem to have replaced the other in an irregular manner along the lines of stratification, shreds of one projecting into the other. Under the microscope the change in appearance is seen to be due to the change from an amorphous silica to a crystalline variety, the dull portion of the rock consisting almost wholly of non-polarizing silica, while the clear portion polarizes. This is not a local character but has been observed by the writer in many portions of the Coast Ranges where the Miocene flints occur. This change must be associated with that which led to the deposition of the chalcedonic silica in the little veins which traverse the flints.

Several sections prepared from the light yellow or white shale gave interesting results. In these cases the greater part of the surface shown consisted of a granular isotropic aggregate. Mingled with this were polarizing grains and round spots filled with a brightly polarizing silica similar to that in the first section. A number of the circular areas exhibited an organic structure, and are referable probably in part to foraminifera and in part to radiolaria. There were a few clear, rectangular, elongated areas of small size which polarized strongly, and extinguished parallel. There were also a few irregular areas resembling in outline fragments of volcanic glass, but this could not be decided with certainty. These were the only indications of volcanic material in the rock. Not only is the amount of material small, which could with any certainty be referred to volcanic origin, but there were detected no particles of clastic origin.

Chemical Character.—A specimen of the white porcelain-like shale was taken for analysis* (I). It is easily scratched with a

* All analyses in this paper, unless otherwise stated, are by the author.

knife, and breaks with a conchoidal fracture. The microscopic slide showed numerous organic remains, as before described. It contains no carbonates. It is interesting to note the close resemblance of this analysis to that given by Lawson and Posada,* of the white bituminous shale at Monterey (II). Another analysis (III) was made of an opaque flint; and (IV) is the percentage of silica in a clear black flint.

	I.	II.	III.	IV.
SiO_2	86.92	86.89	92.37	98.1
Al_2O_3	4.27	2.32	2.46	not det.
Fe_2O_3	....	1.28	....	" "
CaO	1.60	1.43	1.70	....
MgO	trace	trace	....	....
K_2O	2.48	1.26	....	....
Na_2O		2.32	....	....
Ig.	5.13	4.89	2.74+CO_2	....
Total	100.40	99.39	99.27	....
Sp. gr.	2.12	1.8 to 2.1	2.54	2.57

The organic remains in No. I, if they ever were calcareous, have had the carbonate entirely replaced by silica. The following experiments were carried on for the purpose of determining the nature of the silica in these rocks, and whether the amorphous material in the flint and shale was really colloid silica or an aggregate of minute fragments of an acid volcanic glass. A gram of the white shale was finely powdered and treated with a strong solution of caustic potash for two days, with the result that all but 11 per cent of the powder dissolved. An equal amount of powdered pumice was then treated in the same manner, with the result that it lost a small fraction of one per cent. This proves that the amorphous material in these rocks is of the nature of opaline or colloid silica. A slide of the chalcedonic flint treated with a solution of the alkali was not affected. A specimen of the bituminous limestone which appeared to consist almost wholly of minute organisms, yielded with a rough test about 60 per cent of calcium carbonate, and 20 per cent of

* Bull. Dept. Geol. Univ. Cal., Vol. I, p. 25.

water and organic matter. The residue appeared to be of an aluminous nature rather than silicious.

Origin of the Shales.—The bituminous shales (Monterey series) have already been studied by Professor Lawson.* The view was tentatively advanced by him that the white shales were chiefly of volcanic origin. This view is based upon three considerations: (1) The general poverty of silicious organisms; (2) the chemical analysis corresponding rather to an acid soda rhyolite than to an organic deposit; (3) angular fragments of an acid volcanic rock scattered through the groundmass. The evidence seems to show that the character of the silica in a part of the flints or silicious shales is not an original one, but that the present chalcedonic variety has been produced from the amorphous by a molecular change subsequent to deposition and solidification. The colloid or opaline character of the silica at the time of deposition being recognized, the question to be decided is, whether it was formed merely as a chemical deposit from ocean waters holding silica in solution, without reference to any organic origin, or whether it represents the wholly or partially disintegrated silicious tests of organisms which once abounded in this part of the ocean. The fact that in different specimens, and sometimes in the same one, all stages of obliteration can be noted, from those in which the structure is discernible to those which appear as faint dots, gives support to the view that the silica was derived chiefly from disintegrated organic remains. The question is, as Professor Lawson admits, a very difficult one. Our knowledge is too limited to say with certainty what transformations sea water is capable of working out through a protracted interval and at a considerable depth. The bituminous shale has an extensive areal development in the Coast Ranges. Its greatest thickness is not known. Professor Lawson estimates it at 2,000 feet at Monterey.† It is probably 1,000 feet at Point Sal. There are other areas in Monterey County where it is possibly 2,000 feet, and until the whole region is better known, any conclusion reached at present is liable to need revision.

---

* Bull. Dept. Geol. Univ. Cal., Vol. I, p. 26.

† *Ibid.*, p. 29.

With regard to the flinty beds which reach 100 feet or more in thickness in some places, and in others are scattered in thin bands through the somewhat chalky strata, it must be admitted that the presence of the circular areas, undoubtedly of organic origin, favor the view that the beds are almost entirely of such origin, the solvent power of the sea water during and after the slow formation reducing the silicious tests to a structureless mass. There seems to be considerable evidence that the less flinty strata containing alumina and alkalies are in part of volcanic origin, but it does not seem to the author possible that the bulk of these rocks was thus formed. At Point Sal, in the lower Miocene, several thousand feet below the bituminous shales, there are three strata made up wholly of volcanic ash. The volcanic character is most strongly pronounced, and it would seem reasonable that if volcanic ash played an important part in the formation of the silicious rocks, which are considerably younger, it would somewhere be clearly recognizable. The great thickness of the bituminous shales with a fairly constant character would demand an exceedingly prolonged and continuous eruption of great magnitude, of which we have discovered no other record. In the San Antonio Valley, in Monterey County, there is quite an abrupt transition from a coarse arkose sandstone below to the bituminous shales. The strata are conformable, and it would appear that the beginning of the period of deposition of the shales must have been coincident with a depression which probably removed the shore line to a considerable distance, as the fragmental material of the sandstone is entirely absent from the shales. On Point Sal it was a change from beds of clay which in all probability were being deposited at no great distance from a shore line. That this change was not to abysmal depths is indicated, not only by the conformability with the beds below, but by the abundant organic remains which have given rise to the immense quantities of bituminous matter found more particularly in the calcareous portions of the strata.

The less silicious portions of the shales at Point Sal are distinctly seen to be made up of organisms of a calcareous nature. In the thin section no definite forms are visible. Scales and fragments of fish occur everywhere except in the most silicious rocks. The only

distinguishable mollusc is *Pecten peckhami*, Gabb. The change from silicious to calcareous deposits through a series of beds in which waterworn fragments are absent, and microscopic organisms abundant, is due, doubtless, to a change in the conditions of ocean life.

Gypsiferous Clays.—The beds which come under this division, though possessing a varied character, differ markedly from the bituminous shales. They consist of gypsum-bearing clays prominently developed along the southern slope of the main ridge, where they reach a thickness of at least 1,800 feet. Immediately below them lies the most important of the three strata of volcanic ash. Below the ash there is a thickness of nearly 2,000 feet of soft arenaceous sandstone, shale, and conglomerate. The greatest thickness of these beds is exposed in the first cañon east of the Chute. The conglomerates at the bottom alternate with beds of very soft sandstone and consist of pebbles of sandstone and jasper identical in character with the rocks of the Coast Ranges, which the author believes are of pre-Cretaceous age. These pebbles predominate, but there are also present in abundance others of a basic eruptive, probably serpentine, but so oxidized that they appear as round red bunches. They give a characteristic color to the basal portion of the series. Pebbles of gabbro are also present in places. The conglomerates rest on the diabase and gabbro, dipping north at an angle of 50° to 60°. Faulting was not noticed in the cross section east of the Chute, but along the coast from Point Lospie to the teschenite cliff, near the Old Landing, the beds are faulted and folded in short waves. The clays proper extend northwest to the spot where the landing was located. Here they have been intruded by the teschenite dikes. Owing to the friable nature of the latter rock and the very steep slope, slides are constantly occuring in wet weather. These lower Miocene beds are exposed for a mile and a half along the coast north of Point Sal, being overlaid by the Pleistocene. They have much the same character as on the south side of the ridge. They rest against the spheroidal basalt at a very steep angle, and have been so greatly compressed and folded that the thickness could not be estimated. Near the base the sandstone is filled with concretions three to six inches in diameter. They stand out so thickly on the bedding surface of the upturned

sandstone that it presents the appearance of having been peppered with balls. No recognizable fossils were found in any of these beds, with the exception of scales and fragments of fish.

From what is known of the geology of the Coast Ranges it would appear that the basal portion of the beds embraced under the designation Gypsiferous clays represents as low a horizon as has yet been detected in the Miocene.

No outcrops of the jasper beds and associated sandstone are known within many miles, and the presence of numerous pebbles of that series in the conglomerates on the northern side of the gabbro area would suggest the possibility of the existence, during a portion of the Miocene, of a land area to the south from which the fragmental material could have been derived. A gradual subsidence of this area as the period of the deposition of the upper Miocene beds of Point Sal approached would account for the fact that the silicious rocks of the bituminous shales on the south rest directly on the serpentine.

Gypsum Deposits.—In years past, Point Sal was the most important center for gypsum mining in the state. The chute was built just south of Point Morrito, for the purpose of loading vessels. The gypsum occurs in bunches and irregular veins scattered here and there in the soft clays. The clays have the same character as elsewhere in the Miocene of the southern Coast Ranges. They are richly impregnated with calcium salts and alkalies. This fact points to the existence of bodies of water shut off from the open ocean in which the beds were formed. It seems quite possible that in this portion of California land may have existed west of the present coast line.

Volcanic Ash.—There are three strata of a hard, light-colored or greenish rock interstratified in the lower Miocene on the southern slope of the Point Sal ridge. Being so much more resistant to erosion than the Gypsiferous clays, they are among the first features in the landscape which attract the attention. They are finely exposed along the three cañons which cut transversely through the lower hills. The upper bed possesses the greatest extent, reaching from a spot north of Point Morrito southeasterly about two miles, to the valley in which the dairy is situated. It marks nearly the

lower limit of the gypsum-bearing clays. In a branch of the first cañon east of the Chute, it forms a great cliff, for some distance having a thickness of 40 feet. The other two beds are much shorter, the first below being not much over a half mile in exposed outcrop, while the third rests directly on the diabase in the cañon leading up to the dairy. The middle one is about 1,000 feet below the upper, and the third nearly the same distance below the middle. The middle one outcrops prominently on the first ridge east of the Lion's Head, while the third shows a thickness of fully 30 feet where it has been cut by the road below the dairy.

Petrography.—As a usual thing the rock is somewhat porous, a condition due in large part to the thickly disseminated fragments closely resembling pumice. Some portions of the rock are exceedingly compact and almost flinty in character. Scattered particles of a green serpentinous nature are also abundant in places, and give a greenish hue to some outcrops.

Thin sections prepared from the more massive varieties showed a cloudy base, in which are imbedded crystals of feldspar and irregularly shaped isotropic areas which are water clear with the analyzer removed. They are bounded by concave circular or elliptical faces. The meeting points of these faces often appear drawn out in long, slender rods, while still others show a cloudy circular area within. The nature of these fragments is explained not only by the optical behavior, but by the fact that in many cases they contain crystals of feldspar partly within or attached on one side. The cloudy base seems in large part to be made up of the same material, only finely comminuted and undergoing alteration (Plate 2, Fig. 1). In one slide the glassy areas are observed undergoing devitrefication to a clear polarizing aggregate of minute grains which resemble feldspar rather than quartz. That the isotropic fragments are volcanic glass is certain, a glass which was exceedingly pumiceous and frothy. The crystals of feldspar are not waterworn in the slightest manner, appearing with sharp idiomorphic contours. They are twinned on the carlsbad type, though in some cases polysynthetic twinning was noted. The extinction angles vary from 3–6 degrees, indicating an acid plagioclase. No traces of organic remains appear in any portion of these volcanic ash beds, and with

the exception of the greenish serpentinoid fragments, no other material than that of volcanic origin. These beds are quite remarkable in this respect, as well as in regard to the exceedingly fresh condition of portions, and the beautiful symmetrical forms assumed by the glass.

Chemical Character.—An uncovered slide was digested for some hours in a strong solution of caustic potash without producing any apparent effect. A chemical analysis of a very compact specimen gave the following composition:—

SiO_2	74.841
Al_2O_3	12.577
CaO	.983
MgO	.262
K_2O / Na_2O	5.360
Ig	5.273
Total	99.296
Sp. gr.	2.402

Save for the lack of iron, it will be seen that this ash closely resembles in composition many acid rhyolites. Too little is yet known of the geology of the Coast Ranges to enable us to say whether the eruption to which the ash beds are due, can be correlated with any of the acid volcanic rocks which are found in many places. Other beds containing volcanic ash in the form of glassy pumice, are known in the California Miocene, but nowhere else in such thick beds, and so free from foreign material.

KNOXVILLE BEDS.

Occurrence.—The Knoxville appears at two points on the northern slope of the Point Sal ridge. The larger area, which is nearly a mile long, forms almost the whole of the upper portion of the valley of Corralitos Creek lying east of the spheroidal basalt. The other outcrop is much smaller, occurring in the same valley a half mile below the lower dairy. The larger area extends up to within 100 feet of the summit of the ridge, reaching an elevation of 1,050 feet. The character of the beds is identical with that of the Knoxville,

arther north in the Coast Ranges. There is a predominance of he same dark, soft shales, with a subordinate amount of thin-bedded andstone. As a general thing the beds lie nearly flat, although in laces they have been considerably disturbed. When tilted, they trike east and west, with a predominating dip to the north. A num- er of poorly preserved specimens of *Aucella piochii*, Gabb, were ound in the shale. The smaller outcrop down the valley contains nore sandstone with some conglomerate, and has an apparently orizontal bedding. The *Aucella* was found here in the sandstone.

Relation to the Spheroidal Basalt.—The relation existing between he Knoxville and the spheroidal basalt was not satisfactorily ettled. A small laccolite like boss appears intrusive in the larger Knoxville area, but it is a question whether it belongs to the same ruptive body so prominent west of the Knoxville. The small ruptive mass within the latter has considerably metamorphosed ie shales, but the large body of basalt and related rocks to the 'est has, as far as could be detected, no effect upon them. A mall outcrop of conglomerate was seen not far from the basalt, nd a similar conglomerate was quite prominent at the small out- rop down the valley. As the high basaltic ridge rises between hese two outcrops, it is possible the conglomerate might indicate shore line, although no fragments of the basalt could be found. Iowever, the presence of similar occurrences of spheroidal basalt n the older uncrystalline rocks of the Coast Ranges, and the ntire lack of disturbance and metamorphism in the adjoining hales, makes it seem highly probable that the basalt antedates the Knoxville.

AUGITE-TESCHENITE.

Occurrence.—The type of eruptive rock to which the term ugite-teschenite is given, is identical with that previously described y the author under the name Analcite Diabase.* The dikes of his rock are confined to the southern slope of the ridge east of the Old Landing. The slope is so abrupt here that, owing to the soft ature of the Miocene clays, and the disintegrated condition of he teschenite, slides are constantly occurring, and the exact loca-

*Bull. Dept. Geol. Univ. Cal., Vol. I, p. 273.

tion and extent of some of the outcrops indicated on the map are problematical. There are two dikes in the steep face of the cliffs back of the landing, and possibly one on the beach near it. The most important outcrop, which furnished the best and most varied material for study, is that forming the first precipitous point southeast of the landing. The dikes outcrop along the coast for nearly a quarter of a mile with steep cliffs, 200 feet high. The largest dike begins a little back of the point just mentioned, and extends in a southeasterly direction for a mile and a half. The road has been graded into it near the landing, while further on toward the east, it is shown in the cañon of Wood's Creek, and in the next gulch a half mile to the southeast. It finally terminates in a small outcrop near the head of a stream flowing into the ocean east of the Chute. All the dikes are intrusive in the Miocene, as were also the other occurrences described in the former paper. The contact metamorphism is clearly shown in the first gulch east of Wood's Creek. The dark clay shales and sandstone dip northeasterly at an angle of 30°, and have been intruded along the bedding planes. The strata show an alteration for a distance of 75 feet. For the first 10 feet the metaphorism has been sufficient to turn the shale into slate. The alteration is nearly equal to that produced by the Cuyamas dike. In the cliffs above the landing the dikes are also apparently conformable with the dip of the inclosing shales, which is also to the northeast. The eruptive mass at the big bluff has cut through the shales, and at the top they rest partially on it. Boulders of the teschenite also occur at the foot of the cliffs opposite the seal rock, and it is possible that the rock of the little island may belong with this group.

Macroscopic Character.—The individuality of this rock type as it occurs in the field is most striking. Point Sal is the fourth locality where it has been found, and, although marked variations occur, yet it has in general such a characteristic aspect that it is not easy to confuse it with the other basic rocks of the Coast Ranges. With the exception of a part of the large outcrop on the cliffs, the Point Sal teschenite is a rather dark rock, often showing the different components indistinctly. Near the surface, with the exception of numerous hardheads, the rock is exceedingly friable,

being perfectly disintegrated and ready to fall in pieces on exposure. Where the cañons have cut across, it is somewhat harder, but has even there the appearance of considerable alteration. Feldspar and augite, the latter in fresh, lustrous crystals, appear in the hand specimen, in addition to analcite and other alteration products. It is, however, in the large outcrop in the cliffs that the rock is best exposed in all its interesting facies. Although the cliffs are nearly 200 feet high, the rock at the bottom where the waves are eating into it seems fully as decomposed and disintegrated as that near the surface.

While there are portions of the mass which are solid and apparently fresh, as shown by the large boulders at the foot of the cliffs, much of that even at the shore line gives a dull thud when struck and crumbles with a slight blow. The variation in structure and general appearance in this outcrop is remarkable. An aphanitic gray specimen from the edge of the mass has the appearance of being sporadically amygdaloidal. Toward the northern side there are areas of considerable size in which the rock very closely resembles the Cuyamas eruptive. It is a coarse, light-colored rock, with lath feldspars, dark, lustrous augites, and abundant analcite in large grains. This light-colored rock is often more coherent and seems to shade off into the darker and more friable portions insensibly in places, in others to project into it in dike-like tongues with quite a noticeable difference. The contrast is sufficiently strong in places to make it appear as if one were intrusive in the other. In most places the distinction between the more coherent and that less so, and between the coarse facies and the finer grained, is not sharp. A large area in the center of the outcrop has a peculiar character. This consists in the presence of nodular kernels of fresh, hard rock imbedded in a decomposed matrix of apparently similar composition. A close examination showed that these nodules, averaging perhaps a half inch in diameter, were as a rule each composed of a poikilitic augite crystal filled with minute lath feldspars. This was made apparent by breaking one, when the fracture would be seen to be a cleavage plane of the augite. No sharp demarkation appears to exist between this rock with the poikilitic structure and that with the panidiomorphic. So abundant is the feldspar in the augite that

the structure is not noticed until shown by reflection from a cleavage plane. In this facies the feldspars are invariably very small, while the augites occasionally reach a size of 1.5x1 inch. The lines of weakness in the rock, or those along which greater alteration has taken place, seem to lie between the augites. The large boulders strewn along the base of the cliffs almost always weather with pitted surfaces due to the aggregation in bunches of some more easily decomposed constituent. In some cases the softer spots consist largely of greenish material, which, however, appears to be distinct from the augite. In other rocks the lighter-colored portion appearing in nodular forms several inches in diameter, weather away more rapidly.

The surface of the cliffs is far from having a uniform appearance. In addition to the variation in color there appear large irregular bunches or ramifying dike-like masses of rock which are much more coarsely crystalline. In some cases these appear sharply differentiated from the body of the rock; at others they gradually blend into it. Scattered through portions of the coarser rock, and in the centers of the ramifying dike-like masses, are cavities which are lined with finely crystallized analcite. The crystals are clear and often perfectly formed, showing the common trapezohedral shape. This type does not seem to have been subsequently intruded but to be a kind of segregation from the magma, cooling more slowly, and probably formed after the consolidation or partial consolidation of the main mass. It might be due to strain set up in the partly consolidated magma resulting in a partial refusion and followed by slow cooling.

The dike-like masses of somewhat lighter color ramifying through the dark rock at first sight appear like true dikes, but upon close examination they present a different character. They are generally very coarse, with large augite crystals standing on their borders perpendicular to the walls and interlocking with the constituents in the inclosing rock. There is no sharp line between the two. Some of the augites reach a length of four inches and a diameter of over a half inch, frequently showing idiomorphic boundaries, and inclosing a correspondingly coarse mass of feldspar. The central portions of these areas of coarse crystallization, which it

seems to the author might properly be termed "segregated veins," are often finer grained than the exterior. Analcite is abundant in large masses sometimes two inches in greatest diameter, either completely or partly filling spaces apparently left between the other constituents, in the latter case being well crystallized. These spaces sometimes occupy the centers of the bunchy areas, in which there is a gradual increase in coarseness from the normal toward the center. The centers of the coarse crystallization, now empty or filled with analcite, might conceivably have been left as spaces and subsequently filled, or possibly occupied by a residual portion of the magma, which the author believes is represented by the analcite scattered through the rock in the polyhedral areas. There is another set of veins, or more properly dikes, which are undoubtedly of subsequent intrusion. This took place probably while the mass was still hot, for they are fairly coarse grained, though only a few inches in diameter. They are similar in appearance to the lighter portions of the rock, though occurring only in the darker. Sometimes distinct clearly defined nodules appear which seem like inclusions. One type of the rock is almost jet black, with lustrous augites and feldspars. Angular pores are numerous and lined with a soft decomposition product. They must be due to the partial removal of some constituent. Analcite is not visible to the unaided eye in the most of the darker facies of the rock, although its original presence is clearly indicated by the surface weathering. It seems probable that some of the larger cavities occupied by the analcite may be of secondary origin, but this question is difficult of solution.

Microscopic Petrography.—Many specimens were obtained from the large boulder-like masses at the foot of the cliffs which were apparently very fresh, and it was hoped that in some of them direct evidence could be obtained of the primary condition of the rock, for it is believed that the analcite, everywhere so abundant, has replaced a soda rich silicate, probably nepheline. Although many sections were prepared, no nepheline could be found, but there was accumulated a mass of evidence, indirect in its nature, yet still of such importance that it seems to the author that there can no longer be any doubt that the analcite has replaced a primary soda mineral.

The rock varies in structure from holocrystalline, approximately panidiomorphic, to ophitic. In the ophitic varieties the separate augite patches appear optically and crystallographically orientated the same over large areas, sometimes more than an inch in length and nearly as broad. Gradations take place from this type, in which the augite individuals are so disseminated as to almost meet and have an ophitic character, to one in which the portions are united to form true poikilitic crystals inclosing scattered feldspars. In the panidiomorphic facies the feldspars occur as long laths or in tabular form and much more coarsely crystallized than in the ophitic. The order of crystallization has been as follows in the panidiomorphic facies: augite, apatite, feldspar, magnetite, and the mineral, probably nepheline, which the analcite has replaced. In the ophitic facies the order is, apatite, feldspar, magnetite, augite, and analcite.

The apatite is recognized in all facies of the rock as very slender prisms, extinguishing parallel and possessing a hexagonal cross-section. It penetrates both the feldspar and analcite, but not the augite.

The feldspar is very similar to that from Cuyamas, showing the same zonal structure and alteration products. The extinction angles obtained in the centers of the crystals indicate a basic labradorite.

Nearly all the sections prepared from the coarser material, in which the feldspars appear as short laths and broad plates, showed very marked zonal extinctions. The crystals consist of a mixture in varying proportions of the anorthite and albite molecules, for, while the centers are basic labradorite, there is a constantly increasing acidity toward the outer edge where the albite molecule is present to the exclusion of the anorthite. It would appear from the examination of many slides that the core of the crystals, embracing about two-thirds of the total diameter as viewed in lath-shaped sections, extinguished nearly simultaneously, but that then there occurs a sudden transition to an acid plagioclase. Taking a section in which the centers of the adjoining twin lamellæ extinguish symmetrically at $+26°$ on opposite sides of the cross hair, the extreme outer rim became dark at $-4°$, that is, on the opposite side of the cross hair. The alteration of the feldspars exhibited in the different types

of the rock is exceedingly variable, as is also that in different parts of the same hand specimen. It does not seem to bear any definite relation to different portions of the crystals, being in some instances more pronounced in the rims, in others at the center or along the line marking the transition between the basic interior and the acid exterior. The change to analcite, as in the Cuyamas dike, is very widespread, but other cloudy decomposition products are abundant. In one specimen the alteration appears as a dark almost opaque band running concentrically around the crystals at the junction of the acidic and basic portions. The feldspars inclosed in the large poikilitic crystals are as a rule very fresh, while those aggregated together between the augites, having associated with them the greater part of the analcite, are often reduced, together with the analcite, to an indeterminable cloudy mass. The feldspars are quite fresh in some of the darker rocks which appear much decomposed through the leaching out of the analcite. As a rule the alteration of the feldspar is bound up in the closest manner with the presence of the analcite. The feldspars within the augite, comparatively free from contact with the analcite, are fresh; while without, where the most of the analcite occurs, the alteration is often extreme.

Twinning occurs on the albite law, though in some cases it is combined with the carlsbad law. The twins consist of broad and narrow plates. The feldspars in the poikilitic augite crystals are in the form of small laths, sometimes not averaging more than a millimeter in length. They occur either singly or in aggregates. With an increase of the feldspars in the augites there is a transition to the ophitic structure, where the feldspars are distributed nearly evenly through the rock. In one section a linear arrangement of the feldspars is very noticeable.

An interesting micro-pegmatitic intergrowth is present in one of the coarser dark facies (Plate 2, Fig. 2). This is probably secondary and is taking place on the borders of the broad feldspar plates. It is an intergrowth of two feldspar individuals differently orientated. In some cases it has to a considerable extent replaced the original feldspar. The outer portion of this intergrowth is made up of large areas, irregular in outline, but becoming smaller towards the heart of the original crystal, and terminating along crystallographic

planes. One set of areas extinguishes with the unaltered crystal, while the other makes varying angles with it. In some cases this granophyric growth has been from the outer border of the crystal into the angular spaces originally occupied by the analcite. In this case neither set extinguishes with the adjoining crystal of feldspar, but one blends into it as the stage is revolved in the same manner as the basic core of the crystals gives place to the acid rim.

In many respects the pyroxene of these rocks closely resembles that of the Cuyamas eruptive. In thin section it is a pale brownish green basaltic augite, showing no pleochroism. It has a bright almost metallic luster, and is, in most cases, very fresh. It differs from the augite described by the author in the Cuyamas eruptive in showing no diallagic cleavage, but has the peculiar parting so closely resembling normal twinning. In only one instance was there noticed any alteration, and that was a change to green hornblende. In the panidiomorphic facies the augite occurs as long slender individuals with octagonal cross section (Plate 2, Fig. 3). Terminations consisting of the basal plane and orthodome were sometimes observed. The extinction angle is very high, approximating 54°. Many sections were obtained in the different slides cut parallel to the *c* axis, and a surprisingly large number gave high angles of extinction. Twinning is very common, the composition plane being the orthopinacoid. The peculiar parting plane described in the Cuyamas eruptive is frequent. Physically this in every way resembles the composition plane of ordinary twins, but differs in the fact that the two halves always extinguish simultaneously. No reason was found for doubting the conclusion reached before that it might be explained by the supposition that there is here a juxtaposition of two individuals similarly oriented. It is quite possible that they may be separated by a lamellar twin of such thinness as to be indiscernible. A large number of twins were observed in which the difference of extinction of the two halves was 3° to 10°. There is a gradual transition from the idiomorphic augites to the ophitic and poikilitic. In the latter the crystals seldom touch each other, but are separated by the greater part of the feldspar and analcite. The poikilitic crystals contain both magnetite and analcite in addition to feldspar. The analcite is not as abundant as in the feldspar matrix between the augites (Plate 2, Fig. 4).

A substance which is undoubtedly the decomposition product of olivine is present in several of the slides, prepared from the darker facies of the rock. It varies in color from reddish brown to green. The polarization colors are quite high, and the extinction is parallel to the cleavage cracks.

Magnetite is fairly abundant in the rock. The ophitic variety generally contains less than the panidiomorphic. In the latter it has quite generally been formed subsequent to both feldspar and augite, being allotriomorphic with reference to them (Plate 2, Fig. 3). Masses of magnetite are frequently aggregated in certain portions of the section in a manner precisely similar to that of the augite in the ophitic structure. The grains fill angular spaces between the small lath feldspars, each group probably being referable to one individual. In the ophitic facies it often crystallized between the periods of the feldspar and augite. A remarkable aggregate of skeleton forms was observed lying partly within an augite crystal and partly in a mass of decomposed feldspar and analcite. The magnetite differs from that of the Cuyamas eruptive in that titanium is absent.

Analcite is by far the most important of the secondary products present in the rock. Although it is not visible to the unaided eye in many of the hand specimens, yet the microscopic examination shows that it was probably once present in all. In places it is now represented by other secondary products which have often been more or less leached out, giving the rock a porous aspect. In many slides it is shown to have replaced the feldspars to a considerable extent, being scattered through them in the most irregular manner. The difference in composition in the different portions of the feldspar crystals seems to have no effect upon the degree of alteration. In one crystal it may be more pronounced in the central part; in another the outer shell has undergone the greatest amount of alteration.

The most interesting question is raised by its occurrence in the polyhedral or wedge-shaped areas between the other components. Upon the correct determination of the significance of its presence here rests to a large extent the classification of this peculiar rock type.

In the light-colored, more coarsely crystalline portions of the

dike, it is apparently as abundant as in the Cuyamas eruptive. In the poikilitic facies, however, where the feldspars are very small, the angular areas occupied by the analcite are correspondingly small, and it is not visible to the unaided eye. There are large areas of the rock also where it has been replaced by decomposition products. The microscopic examination shows that in the coarser rocks it has undergone but little alteration. Greenish products appear, as well as those referable to natrolite. The latter forms cloudy radial aggregates. The finer-grained rocks probably contain fully as much analcite, but it is often disseminated in such small areas that it is not at first noticeable. These smaller areas have undergone alteration more easily, and, as a consequence, fresh analcite is rare. Natrolite is perhaps its most common alteration product. It occurs associated with the feldspar within the poikilitic crystals of augite, but is particularly abundant in the feldspar aggregates between them. Its abundance in comparison with the feldspar is somewhat less within the augites than between them, where it often forms nearly one-fourth of the area. A dozen small polyhedral areas of analcite or natrolite were counted within one augite individual, occurring in the same manner as in other portions of the rock, that is, filling spaces probably once occupied by a residual portion of the magma (Plate 2, Fig. 4). These areas are frequently in contact with the augite, being bounded in part by that mineral and in part by the feldspar. It seems to the author that the presence of the analcite, showing this relation to the large augite individuals, is of the greatest importance in aiding us to reach a true conception of the original condition of this peculiar rock. Not only is it a fact that an original miarolitic structure has never been seen in rocks of the diabase class, but it is improbable that the spaces within the augites should ever have been left as empty cavities. These areas, as cut by the section, are wholly inclosed in the feldspars, or are scattered in bunches through the augite, or are bounded by both the augite and the feldspar. The bounding plane of the augite in the last case always appears to be a crystal face, and has that regularity which would be expected if the area now filled with analcite were at the time of crystallization filled with an unconsolidated residual portion of the magma. One instance was noted in which

a long, irregular area of analcite, partly bounded by small feldspars, projected into an augite crystal, its shape being determined by the crystal planes of the augite on either side and by the feldspar crystals terminating it (Plate 2, Fig. 6). An illustration of a peculiar occurrence of analcite, or rather its decomposition product, natrolite, is given in Plate 2, Fig. 5. The augite contains aggregates of jagged feldspar crystals, and in one spot, lying parallel to the vertical axis, an area of natrolite nearly one millimeter wide, and about six long. Its sides are formed of crystallographic planes, while feldspars divide it into several parts. It seems to the author that no better indirect evidence could be desired of the original presence of some soda rich mineral. The alteration of the feldspars in many portions of the rock seems to bear a direct ratio to the abundance or paucity of the analcite. Where it is abundant between the augite crystals the feldspars are extremely altered, but within the poikilitic individuals they are often perfectly fresh.

Calcite and pyrite are occasionally present. The rarity of the former is hard to understand in a rock rich in a lime-soda feldspar. The composition of the secondary products derived from both the analcite and the feldspar must be quite varied, and their physical character is such that exact determinations are impossible.

Chemical Character.—A study of the chemistry of the rock is connected with many difficulties, owing to the abundance of secondary products, but at the same time it is believed that results of importance have been obtained. A specimen of rather coarse texture and panidiomorphic structure was selected for analysis (I). It bore a considerable resemblance to that from Cuyamas, the analysis of which, by Mr. Lehner, was given in the previous paper, but which will be introduced here for comparison (II).

	I.	II.
SiO_2	49.61	50.55
Al_2O_3	19.18	20.48
Fe_2O_3	2.12	2.66
FeO	5.01	4.02
CaO	10.05	7.30
MgO	4.94	4.24
K_2O	1.04	2.27
Na_2O	5.62	8.37
P_2O_5	.27	not det.
SO_3	trace	....
Ig.	3.55	H_2O .44
Total	101.39	100.33
Sp. g.	2.782	

It will be readily seen that the two rocks are very closely related. The large amount of water in that from Point Sal is characteristic of the teschenites of Europe. The water is not indicated in the second, although it is certain that about the same amount must be present. It appears that the Cuyamas rock is somewhat richer in soda and poorer in lime. The two occurrences are about 75 miles apart. Although it seemed conclusive from the results of the former study that the high percentage of soda could be accounted for only by postulating its derivation from a soda rich mineral, yet this was not actually proved. Consequently in the present study it seemed best to attempt an isolation of the different components for the purpose of making an analysis of each. This would settle definitely the question if the large percentage of soda could be derived from the feldspars, or whether its source must be looked for elsewhere; for the analysis of the augite material was taken from the large crystals in the coarser facies of the rock. Fragments of feldspar were broken from a coarse specimen, the microscopic examination of which showed it to be comparatively fresh. These fragments were powdered sufficiently fine to pass through a 60-mesh sieve, and then introduced into Klein's solution, possessing a specific gravity of 2.60. With this density, more than half of the material still remained suspended. In order, if possible, to get rid of any

ontaining analcite, the specific gravity was increased to 2.63. That hich remained at the bottom was drawn off, dried and carefully icked over with a needle to get rid of all grains to which augite plinters were attached. The specific gravity of a number of the rains was then taken, and it was found to range from 2.63 to .67. The optical properties of the feldspar would place it in the asic portion of the labradorite series, and the anomalous specific ravity can only be accounted for by the supposition that all the eldspar is more or less affected by alteration. The analcite for nalysis was selected from the clear crystals filling the large cavities. t is evident that this can not give a complete account of the rock, or in addition to the feldspars partly changed to analcite, there re other hydrated alteration products which make a reconstruction f the rock *in toto* very difficult. Although it is impossible to ach absolutely accurate results, those obtained can be considered ufficiently near the truth to enable the question at issue to be ecided. The three following analyses, (I) of the augite, (II) ldspar, (III) analcite, show the results obtained. No. IV, quoted om Dana, is inserted for the purpose of giving the composition of epheline and showing its relation to analcite.

	I.	II.	III.	IV.
SiO_2	46.59	52.72	54.40	44.08
Al_2O_3	9.69	30.46	23.04	33.28
FeO	4.75	....	....	....
Fe_2O_3	1.03	....	....	....
CaO	21.38	11.01	.21	1.85
MgO	13.89	....	....	....
Na_2O	1.23	3.70	13.33	16.00
K_2O		.42	.19	4.76
Ig.	1.22	1.44	8.46	.45
Total	99.78	99.75	99.63	100.12
Sp. g.	2.338	263–267	2.261	2.6

In the case of the feldspar, the result is very nearly what would be expected from a study of the optical properties. It is probable that the central core is a little more basic and that the outer rim

was wholly or partly excluded in the selection of material. Hen it is reasonable to suppose that the feldspar, as a whole, is a lit more acid than the analysis would indicate. On the supposition that the albite and anorthite molecules have the ratio Ab_1 An_1 it clear that less than half of the soda represented in the analysis the Point Sal rock can be contained in the feldspar.

The pyroxene, as shown by the analysis, is a typical aluminc basaltic augite. The small amount of alkalies is indicative of t absence of the ægirine molecule.

The composition of the analcite agrees very closely with t average of the analyses of that mineral. The smaller areas throu the rock may differ from this to a limited extent. From the analy of the three important constituents it appears that, after deducti the soda from the proportionate amount of feldspar, and consideri the whole of the alkalies in the augite as soda, there still rema to be accounted for about three per cent of soda. This fact ne tives the view that all the analcite could have been leached fr the feldspars to fill original miarolitic cavities. The question th of the origin of the analcite is considerably simplified. It c have but one of two origins. It has either been introduced i the rock after solidification, or it has resulted from the alteration some soda rich mineral, which filled the angular spaces between t other constituents, the last portion of the magma to solidify. more detailed discussion of this question will follow later.

Five grams of the rock were powdered, and a quantitat separation made by means of Klein's solution and the magr This gave the following results: Augite, 32.3; feldspar, 43.3; an cite, 20; magnetite, 4; apatite, estimated, .004. The result, as as the feldspar and analcite are concerned, is only approxima Using the densities of the components, and their relative prop tions, the following table has been constructed. The percentage water in the different components, except the analcite, is deduct as the gravities given, particularly of the augite and the analc are those of the purest material obtainable. The result obtair agrees closely with the actual specific gravity of the rock.

Minerals.	Proportion.	Specific gr.	Estimate used	Product
Feldspar	43.3	2.50–2.67	2.57	1.11
Augite	32.3	3.338	3.33	1.07
Analcite	20.0	2.261	2.24	.43
Magnetite	4.0	5.0 *a*	5	.20
Apatite	0.4	3.20 *a*	3.20	.01
	100	*a* Assumed.		2.82
			Actual specific gr.	2.782

The following table gives the composition of the rock as computed chiefly from the analyses. In place of the analysis of the feldspar, one slightly more acid is taken, corresponding to $Ab_1 An_1$ plus water. The results agree fairly well with the determined composition of the rock as a whole. It is clear that in one where so much alteration has taken place, it is impossible to harmonize the proportions of all the constituents.

	Feldspar.	Augite.	Analcite.	Magnetite.	Apatite.	Computed Composition.	Rock Analysis.
SiO_2	23.18	15.14	10.88	.....	.....	49.20	49.61
Al_2O_3	12.02	3.16	4.61	.....	.....	19.79	19.18
FeO	.....	1.53	.....	3.31	.....	4.84	5.01
Fe_2O_3	.....	.30	.....	1.69	.....	1.99	2.12
CaO	4.21	6.91	.05	.....	.23	11.40	10.05
MgO	.....	4.48	.....	.....	.....	4.48	4.94
Na_2O	2.45	.39	2.68	.....	.....	5.52	5.62
K_2O	.19	.....	.05	.....	.....	.23	1.04
P_2O_5	.....	.....	.....	.....	.27	.27	.27
Ig.	1.25	.39	1.73	.....	.....	3.37	3.55
Total	43.30	32.30	20.00	5.00	.40	101.09	101.39

Petrographic Relations.—The main object of the detailed chemical study was to gain some help in reaching a correct view of the original composition of the rock. In the case of the teschenites of Europe, it is believed by many that the analcite has been formed wholly at the expense of the feldspar, and that there is no evidence of its having replaced a soda rich mineral such as nepheline. Although Rosenbusch, Teall and others have held the view of the original presence of nepheline, the general tendency has been to narrow the group, and of many to consider all teschenites as only varieties of diabase. The question has to be decided, of course, on the presence or absence of nepheline, and upon the meaning of the

large percentage of soda in a rock containing a lime-soda feldspar. But for the excess of soda, the composition of the rock and its structure would, of course, place it with the diabases. In the case of the rock under investigation, the analcite must have one of two sources: it either represents a primary soda mineral, or it has been introduced into the rock subsequent to solidification. If the latter is the case, the structure must have been originally miarolitic, for the areas occupied by the analcite are bounded by crystals with idiomorphic faces. For the purpose of realizing what this supposition involves, the following considerations will be of value. In the first place, the miarolitic structure has never been observed in the diabases or related rocks, and if we except the presence of the analcite, it must be acknowledged that this rock is a typical diabase. The conditions under which a similar structure, possibly miarolitic, occurs both at Point Sal and in the Cuyamas region, are exceedingly varied, and it is impossible to believe from what we know of the relation existing between structure and circumstances of cooling magmas that it would be the same in all cases. In the case of the Cuyamas eruptive, there is one large mass, 1,000 feet across, cut by numerous dikes, some no wider than six inches, all of which show the same angular areas filled with analcite. At Point Sal there is a greater variation still. The angular spaces filled with analcite and its decomposition products are to be seen in all the facies from the coarse panidiomorphic through the ophitic to the fine-grained aphanitic edges. Dikes two to three inches across of a rock approximately panidiomorphic contain analcite under the same conditions as the inclosing rock, which is ophitic. In addition the latter facies contains analcite, occupying angular spaces within the large augite crystals under circumstances which certainly preclude the supposition that they are miarolitic cavities. It is impossible to believe that empty polyhedral areas, not having the form of negative crystals, should have remained within the augite during its segregation and crystallization, even though we allow the possibility of such miarolitic spaces in the body of the rock. In the case of one of the Cuyamas dikes there occur clearly defined hexagonal areas which are filled with analcite. There is no possibility of their being referable to apatite, and they are explainable only on

the supposition that they represent a primary constituent altered to analcite.

If there is a strong improbability of the existence of original miarolitic spaces in this rock, the view of the subsequent introduction of the analcite is thereby weakened. For the latter view to have any probability at all, it is first necessary to demonstrate the probability of the existence of a porous rock.

There is an objection, however, of considerable weight of a wholly different nature, which might be used against the views just presented. This concerns the chemical composition of the augite. It may be argued that a magma which was originally rich in soda would necessarily have produced an ægirine or an ægirine-augite, and that with the presence of a normal basaltic augite, there is good reason to believe that the magma contained but little soda. There is the fact also that the augite has apparently the same character whether its period of crystallization was coeval with or followed that of the feldspar. In the poikilitic facies the feldspars are all small, and do not show zonal extinction, and it is possible that in the two types the relative periods of crystallization did not differ as much as might be expected from the marked difference in structure.

It is a fact which has been emphasized more perhaps by Brögger than any one else, that the ægirine molecule plays an important part in the composition of the augites of the nepheline-bearing rocks. The question whether it is invariably present in the augites of such rocks is an important one, and would have great weight in disproving the author's views if it should appear that such is the case. Rosenbusch* says: "All nepheline rocks contain a basaltic augite as the most important component besides nepheline. In nepheline rocks the augite is characteristically accompanied by a red brown to blood red biotite, more rarely by ægirine or amphibole minerals." In the last edition of his "Mikroskopische Physiographie,"† he says: "Akmite and ægirine appear to be confined entirely to the eruptive rocks, and especially to arise in the magmas

* Mikroskophische Physiographie der Massigen Gesteine, 2d edition, p. 782.

† *Ibid.*, Vol. II, 3d edition, p. 538.

rich in alkalies. They have been recognized in the soda rich granites and syenites as well as in the eleolite syenites. Among the younger eruptive rocks it is the phonolites and leucitophyres as well as related rocks in which occur ægirine or the nearly related acmite, or, expressed more truly, the monoclinic pyroxene rich in the acmite molecule. Ægirinê-augites are regular components of many leucitophyres, phonolites, and eleolite syenites." From these quotations it would appear that the ægirine-augite is not necessarily or even generally present in the basaltic nepheline-bearing rocks.

Zirkel* gives the following account of the occurrence of ægirine: "In the younger eruptive rocks ægirine or an ægirine-like pyroxene, rich in soda, is known in many phonolites, certain phonolite-like trachytes, sanidinites, some leucite and nepheline rich rocks. A relatively high soda content of the magma always appears to be necessary for the crystallization of a soda rich pyroxene." Of the augite of the nepheline rocks he says: "The augite in these nepheline basalts is in general wholly like that of the feldspar basalts." This is sufficient to show that, as far as our knowledge goes, the absence of the ægirine augite does not seriously affect the question of the original presence of nepheline. It would appear that this augite is generally present in the more acid nepheline rocks, but more often absent from the basic varieties.

The history of the teschenites has many features in common with that of other groups. The name was first used by Hohenegger† in 1861 for some eruptive masses in the Cretaceous of central Europe. The group was more narrowly defined by Tschermak,‡ and later by Rhorbach.§ The latter divided the teschenites of Tschermak into two groups on structural grounds, depending on whether the ferro-magnesian silicates crystallized earlier or later than the feldspar. Zirkel‖ accordingly refers the rocks with the latter structure (ophitic), which are less widely spread and contain no

* Lehrbuch der Petrographie, 2d edition, Vol. II, p. 293.

† Geognost. Verhalten. der Nordkarpathen in Schleisen, etc., Gotha, 1861.

‡ Sitzgsber. Wiener Akad., Bd. 53, 1866.

§ Min. u. petr. Mitth. VII., 1886.

‖ Lehrbuch der Petrographie, 2d edition, Vol. II, p. 678.

hornblende, to the diabases. The hornblende, augite-bearing rocks he describes under the term teschenite, although at the same time expressing the opinion that they never contained nepheline and should not be referred to the theralites but to a group intermediate between the diabases and the diorites. Rosenbusch * would refer those varieties of rock earlier termed teschenite to the diabases in which the evidences for the original presence of nepheline is not clear, while those in which nepheline exists or probably existed, he would retain under the original name and classify them with the theralites. Rhorbach † could find no nepheline in the rocks studied by him, and intimates that apatite has been mistaken for nepheline. He says, "All the rocks of this group are characterized by the presence of analcite and other zeolites"—that the feldspars have a kernel of anorthite, and a rim of oligoclase. An analysis of hornblende intergrown with augite is given which shows no alkalies. In some of the hornblende three per cent of alkalies were found, which Rosenbusch thinks plays the part of the ægirine in the Montana rocks.

MacPherson ‡ says of some rocks of Portugal, which he classes with the teschenites, that the analcite occurs in the same manner as quartz in granite, and that it appears to be infiltered into all the elements of the rock, especially into the feldspars. Crystals of analcite appear which are elongated in a manner which seems to correspond to nepheline. He believes that the nepheline is intimately united with the analcite. Of another occurrence (Forte de Alquiedam), "The hornblende disappears wholly, and the pyroxene takes on a diabasic character. The remainder of the rock is formed of crystals of feldspar and analcite." The analcite is spoken of in such a manner as to convey the impression that it has crystal boundaries, and unless occurring in cavities must have replaced some primary constituent. In all the discussions over the teschenites of Europe no writer seems to have thought it possible that the analcite could have been introduced after solidification. Although in many cases its amount seems to be large, those who reject the view of its

* Mikroskopische Physiography, 2d edition, p. 251.

† Min. u. petr. Mitth. VII, 1886.

‡ Bull. Geol. Soc. de France, 1882, p. 292.

derivation from some primary mineral trace it to a feldspar, which, according to all observers, has an average composition as basic at least as labradorite. Zirkel * says, "It is not to be denied that it is difficult to conceive of the alteration of plagioclase which always contains more lime than soda into a soda rich analcite almost free of lime." Rosenbusch † remarks to the same effect, and adds farther: "It remains difficult of explanation how the zeolitizing of a lime rich feldspar results almost exclusively in a soda rich zeolite. . . . The relative quantities of the alkalies and silica make it probable that nepheline was the original constituent."

It seems to the author that when there are taken into account all the facts connected with the occurrence of this teschenite-like type at Point Sal, as well as at other localities in the Coast Ranges, it can not be believed that the peculiarities are due merely to the infiltration of the elements forming the analcite after solidification. It has been shown certainly that it can not possibly have been derived from the feldspars, and to suppose that a miarolitic structure once existed in all phases of the rock under such exceedingly varied conditions demands a stretch of the imagination beyond all scientific bounds.

Although this rock differs considerably from most of the typical teschenites of Europe, yet there are many common features, both chemically and mineralogically, and it has seemed best to use the name already introduced. The only explanation which it appears can account for this peculiar and uniform type of eruptive rocks as known in California, is that there was originally present a soda rich mineral, in all probability nepheline.

BASALTIC INTRUSION IN THE KNOXVILLE.

Occurrence.—A small body of dark basaltic rock appears in the Knoxville nearly in the center of the larger area on the head of Corralitos Creek. The relation of this eruptive boss to the Knoxville is quite remarkable and interesting. The soft shales have been locally tilted up and hardened, and it is due to their more resistant character that the underlying eruptive was discovered. It has

* Lehrbuch der Petrographie, Vol. II, p. 681.

† Mikroskopische Physiographie, 2d edition, p. 252.

forced its way up through the shales, tilting them nearly vertical on the lower side. In the center is a mass of metamorphosed shale sharply folded in a syncline and dividing the outcrop into two parts. On the upper side the shales rise in a gentle swell from a nearly horizontal position, and are exposed in an abrupt wall 3 feet high resting directly on the intrusive body (Fig. 2). The metamorphism is not noticeable for a distance of more than 30 or 40 feet, but in the first 8 feet it is very strongly pronounced, the soft shales being

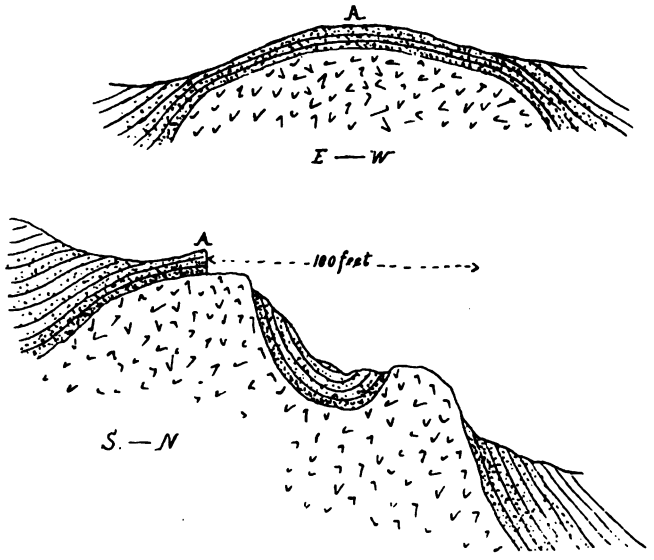


FIGURE 2.—Basaltic intrusion in the Knoxville.

changed to a compact flinty rock. The shales inclosed in the center have apparently only a slight depth, and everything points to the fact that the magma never reached the surface, but has been exposed by erosion in comparatively recent times. The manner in which the strata have been lifted reminds one very strongly of a lacolite, but the relation of the eruptive to the strata below is in all probability not of that character.

Microscopic Character.—The slides prepared for the microscope show a fairly uniform groundmass, in which porphyritic crystals of feldspar and pyroxene occasionally appear. The pyroxene occurs

in fresh almost colorless idiomorphic crystals with no pleochroism. The feldspars of the first generation occur more rarely. They are so completely reduced to a green feebly polarizing mass as to be hardly distinguishable. The groundmass consists of a minutely granular substance of brown color, polarizing like augite, small feldspar laths, often jagged and irregular, abundant magnetite grains, quartz, and calcite. The rock has so changed that it is not certain if glass is present, but the numerous greenish non-polarizing areas may be referable to that substance. Chlorite is abundant in aggregates of small needles. Quartz is present in all the slides, thickly dotted through the groundmass, and is in all cases probably secondary. The slender feldspar laths possess low extinction angles as a rule.

SPHEROIDAL BASALT AND DIABASE-GABBRO COMPLEX.

Field Relations.—Under this head is embraced a series of eruptive rocks forming the main portion of the Point Sal ridge for a distance of nearly three miles. As far as noted, the basalt forms the summit, northern slope, and a part of the southern slope of the ridge. It is almost invariably so decomposed that it was with difficulty that specimens fresh enough for study could be obtained. It is amygdaloidal almost everywhere, and in places the amygdules form the greater part of the rock. The spheroidal basalt with its characteristic features is best exposed in the cliffs north of Point Sal. For half a mile there are clean-cut sections of a dark aphanitic rock which is in part at least andesitic and generally more or less amygdaloidal. Near the northern edge there is a cliff with a triangular-shaped face composed of sheeted lavas dipping northwesterly at an angle of 40°. The different layers have weathered out very distinctly. They are quite irregular in thickness, ranging from six to eighteen inches, so that a pronounced wavy structure is to be seen. Between this cliff and the point the spheroidal character is the most striking feature. The term spheroid is somewhat of a misnomer; for the forms assumed by the lava are rather elongated ropy masses packed over each other in all conceivable positions (Fig. 3). At one spot there is a rude parallelism in the arrangement, and occasionally a fairly spher-

ical form is assumed. These peculiar forms are often not sharply differentiated from the structureless basalt. The marked features of the ropy or spheroidal masses are only brought out distinctly where erosive action has been favorable. They vary in size from a few inches up to three feet in diameter. Where the clean sur-

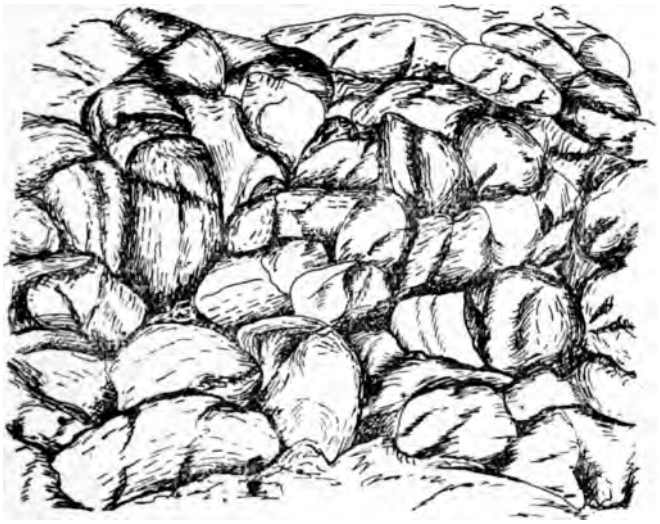


FIGURE 3.—Spheroidal basalt.

faces appear above the reach of the heavy waves, the structure is often apparent. The whole body of a spheroid is in most cases highly amygdaloidal. The outer portion appears to be more resistant, and consequently when they are broken into, a thin shell is left around a partially hollow interior. The outer shell, though fully as amygdaloidal, is more compact and the amygdules smaller. The little rolls are sometimes perfectly massive and structureless, although filled with calcite seams. The amygdules in the basalt are often an inch in diameter and are partly or wholly filled with quartz and epidote. When only partly filled the cavities are lined with drusy crystals. Dikes of an andesitic lava which are slightly amygdaloidal cut through the basalt in the most irregular manner. One dike, of very limited extent but exceptionally decomposed, showed large porphyritic feldspars and contained inclusions of a coarsely amygdaloidal lava.

At the extreme end of the Point the dikes of dark structureless lava become more numerous and on the south side give place to banded or sheeted varieties of varying color. Brecciated dikes of the dark aphanitic basalt are numerous. These are in part perhaps friction breccias, and in part have apparently resulted from the breaking up of partly consolidated flows. The sheeted rocks are cut by dikes of diabase possessing a coarser, more granular aspect. They are bunchy and broken and often terminate in breccias, the dike continuing to grow narrower until it disappears, when its place is taken for a number of yards by the broken rock of the fissure walls. A highly scoriaceous body of dark lava has been forced up through the sheeted rock in places, and above the reach of the waves it weathers out in fantastic cavernous forms. It is often brecciated and filled with epidote. Adjoining one of these bodies is a dike of greatly decomposed but coarsely crystallized rock containing boulders of an amygdaloidal lava. This lava is somewhat similar to that of the volcanic neck a little to the east, and may be continuous with it.

About a quarter of a mile east of the end of the Point, and opposite the seal rocks, a much coarser rock than any yet observed makes its appearance in the cliffs. It cuts diagonally across the sheeting of the basalt which runs parallel to the long diameter of the mountain. The dikes cutting the sheeted lavas have a diabasic structure, while this large body of coarsely crystalline rock which forms the coast line for some distance opposite the seal rocks is a gabbro. It forms the cliffs for perhaps 1,000 feet, and, although slightly finer grained on its edges, presents a fairly uniform character. It is finally displaced again along the upper part of the cliffs by the banded basalt. The latter has an exceedingly gnarled, ragged character, with contorted bands and scoriaceous texture. The cavities are generally empty and sometimes three inches long, while they are twisted in all sorts of shapes. Many dikes, some of them not over three or four inches in thickness, have been intruded in the gabbro near its edges. They vary in color from greenish to almost jet black. The larger ones have a granular diabasic character, while the smaller are aphanitic. Banded or sheeted rocks, similar to those west of the gabbro, replace it toward the east, cutting

across the shore line diagonally. Following these dark rocks the gabbro begins again, but is here very fine grained and almost porcelain like on the edges. As it is traced along the foot of the cliffs, it is found to grow coarser again very rapidly, and in a few hundred feet contains crystals of hornblende a half inch in diameter. Farther along there is a small area in which it is regularly and beautifully banded, a condition due to the arrangement of the light and dark constituents in alternate layers a half inch in thickness. As we follow the shore toward the east, the gabbro is again crowded down to the shore, and for nearly 1,500 feet it appears as a narrow rim near the edge of the water at low tide. The mountain above is occupied by what appears to be the neck of a volcano. Immense masses of lava in various conditions have fallen to the beach. In its essential aspect this rock is a cemented basaltic breccia cut through and through with gnarled and ropy lava injections. Scoriaceous and amygdaloidal boulders appear inclosed in a slag-like matrix. Aphanitic flows of different colors are mixed in confusion with those of a spheroidal character. The twisted and curved rolls are only a few inches in diameter, but not often scoriaceous. Epidote as well as quartz is abundant in cavities and seams. Gnarled, pasty and frothy masses of lava of all colors, yellow, red, green and black, are mixed in the utmost confusion. The whole mass has been seamed with calcite and weathers in the most rugged cavernous fashion. The breaking up of a partially or wholly consolidated magma and its repeated injection by streams of lava has probably taken place in a manner similar to that observed in modern volcanoes.

Owing to the great mass of breccia which has fallen at the base of the cliffs, it is rather difficult to say certainly whether the gabbro has been forced up into the volcanic material or whether the latter is the younger. It seems probable that the supposed volcanic neck is the younger. The massive lava replaces the gabbro wholly in places at the base of the cliffs, as shown by the exposures at low tide. A little farther along and a body of gabbro appears inclosed in the dark aphanitic rocks. It shows the effects of extreme dynamical action in having been reduced almost to a powder, with here and there small nodular masses of hard rock. East of the

volcanic neck the gabbro forms the cliffs and mountain slope above for fully half a mile. It is in this large area that its coarsest texture appears. Crystals of secondary hornblende reach a length sometimes of two inches. The rock mass is not homogeneous in texture, for there are scattered through it, in bunches and irregular veins, coarse aggregates of the main constituents, hornblende and feldspar. Much of the rock has been crushed and in the seams calcite deposited. On some rock cliffs the calcite forms a thickly interlacing network of veins. Occasionally cavities appear in the rock, being probably of secondary origin, wholly or partly filled with clear calcite. Dikes varying in character from those which are dark and aphanitic to those distinctly diabasic abound in various parts of the gabbro. Towards the southeastern edge of the gabbro, but fully inclosed within it, is a large body of sheeted rock of aphanitic texture and varying color. Upon the edge of one sheet variolitic and glassy facies occur.

As the eastern end of the gabbro is approached, it becomes finer and more diabasic in appearance, until, in the cliffs north of the Old Landing, it terminates in long dike-like arms, which extend out into the greatly decomposed aphanitic rocks. It is probable that the gabbro extends underneath the ridge towards the east. The mountain rises above the cliffs, where the gabbro is best exposed, for 1,000 feet very precipitously, and the coarse rock can be traced continuously upward, gradually becoming finer. Near the top there is a sharp transition to the basalt, into which arms of the diabase extend. The cañon west of the lower dairy on Corralitos Creek has cut down through the diabase, as shown by the float.

Age of the Complex.—The field relations are such that the exact age of these rocks can not be determined. That it is greater than the Miocene is certain. That it antedates the Knoxville is probable, for the following reasons: Its relation to the Knoxville is such as to lead to the supposition that it underlies that formation. The great amount of alteration shown in many places is also indicative of age. The spheroidal basalt has a notable resemblance to occurrences through the Coast Ranges which have been described

by F. Leslie Ransome,* and to others noted by the writer, which are supposed to be nearly contemporaneous with the older uncrystalline rocks of the Coast Ranges.

Microscopic Petrography.—As was to be expected from a study of these rocks in the field, the microscope shows that the different structural facies blend into each other. The rocks have undergone considerable alteration, and, even in the case of the comparatively fresh exposures at the base of the cliffs, it is often difficult to tell exactly what the original mineralogical composition was.

The specimens of basalt taken for microscopic study are almost exclusively from the sea cliffs at the western end of Point Sal. But one specimen was obtained from the highest part of the ridge from which a slide could be prepared, and it seemed to be so similar to the basalt at the end of the Point, that there can be no doubt of the geological unity of the whole area of the basalt. In the hand specimen, it appears as a dense rock with the rare occurrence of porphyritic constituents. Under the microscope there are found, in a few slides of the basalt, scattered pyroxene crystals of the first generation. It is an almost colorless, non-pleochroic augite and quite fresh in appearance. The groundmass consists of small lath feldspars imbedded in a matrix of varying character. In the fresher specimens, this consists partly of a finely granular substance polarizing like augite, and probably referable to that mineral, and partly of brownish to greenish interstitial matter having the properties of glass. Nearly all the specimens contain a greater or less amount of green fibrous aggregates. The individuals of these aggregates are arranged radially, so that they show a stationary dark cross as the stage of the microscope is rotated. They are strongly pleochroic, and polarize in yellow, green, and bluish tints, belonging undoubtedly to some variety of chlorite. Many sections show a tendency of the feldspars to separate in two generations, but in none were large crystals observed. The larger of the lath feldspars in the groundmass are sometimes polysynthetically twinned, but more commonly are combinations of two simple individuals. They generally have somewhat ragged outlines, particularly at the extremities. The

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arrangement of the laths is frequently fluidal about the amygdules. The laths sink to exceedingly fine microlites in some facies, so that their outlines are hardly distinguishable. One example was noted in which the mass of the slide is made up of spherulitic feldspars, the field being completely dotted with poorly defined dark crosses which remained stationary on the rotation of the stage. In this matrix crystals of idiomorphic feldspar were disseminated. The extinction of the feldspar laths is generally very small, but occasionally reaches 23°. It is probable that much of the glass of these rocks has become devitrified, as the amount detected is comparatively small. Quartz is very abundant in nearly all the slides. It not only constitutes the chief filling of the amygdaloidal cavities, but is also thickly scattered in irregular grains, apparently filling interstitial spaces between the feldspar microlites. Its secondary character is probable, though there are cases in which it closely simulates primary quartz. Infiltrations of epidote and calcite followed the quartz. Calcite is abundant through the matrix of many portions of the basalt. Magnetite is usually abundant in dusty grains.

The dark massive eruptives which have broken through the amygdaloidal lavas appear under the microscope more nearly related to diabases than to basalts. They consist of a very fine-grained mixture of lath feldspars and augite, which apparently crystallized almost simultaneously. The feldspars have the same extinction angles as in the amygdaloidal rocks. There is a tendency to the development of porphyritic crystals of feldspar and augite which are more nearly idiomorphic. Secondary products such as chlorite, calcite, and quartz are abundant, while no glass could be detected. An analysis of one of these masses, intrusive in the spheroidal basalt, unexpectedly showed a high percentage of silica and little lime, allying it to the andesites. The texture of the dikes cutting the gabbro is coarse in proportion to their size, and they are often much finer on the edges than in the center. A slide made from a dike two feet wide showed an exceedingly fine-grained base, consisting of feldspar microlites and minute grains supposedly augite. In this appear scattered feldspars of larger dimensions. Much of the groundmass is isotropic

A section from the glassy facies of one of the basaltic dikes, near the eastern edge of the gabbro, showed through the most of the slide a pale green isotropic substance mixed somewhat with zoisite and granular secondary feldspar. A hand specimen of a different facies of this dike also appears glassy, and contains, in addition, little pea-like bodies (varioles) four to five millimetres in diameter. This rock consists of an aggregate of polarizing grains, probably a devitrification product. In this were imbedded the indistinctly radial spherulitic bodies which polarize feebly. This is the only spot where a purely glassy facies was noted. The basalt must have been in a state of complete fusion when erupted, and have cooled under almost uniform conditions, as the porphyritic crystals are not numerous or large. The mineralogical composition and structure are remarkably uniform. The almost glassy texture of the dikes in the gabbro indicate that their intrusion was subsequent to the complete solidification and cooling of the latter.

There are numerous transitions between the basaltic dikes and those which, though very fine grained, should, on petrographic grounds, be classed with the diabases. The most of the sections prepared from the diabase contain the ferro-magnesian silicates augite and hornblende in varying proportions. In some cases the hornblende is primary, but, as a rule, it has been formed through the replacement of the augite. Excepting the secondary minerals, all the diabase dikes have a fairly uniform composition. In some cases there is a tendency to the separation of the augite in two generations. A specimen obtained about 500 feet above the water, showed the presence of small granular crystals and aggregates of green hornblende, a little granular colorless pyroxene, irregular lath-shaped feldspars, and granular magnetite. The feldspars show high extinction angles. Another slide contained long, slender crystals of hornblende, often twinned with symmetrical extinction angles of about 15°. A slide from one of the greenish dikes, intrusive in the sheeted basalt north of the seal rocks, contained augite, feldspar, chlorite, zoisite, quartz, and magnetite. The feldspars form irregular laths. The augite, which has a pale brown color, occurs partly in the form of idiomorphic crystals, partly as aggregates of differently oriented individuals, and partly as disseminated grains. The

zoisite has almost the same color as the augite, being slightly more yellowish, and exhibiting a faint pleochroism. It occurs in aggregates of slightly divergent rods with parallel extinction. One of the characteristic green dikes in the gabbro showed no primary constituents. Hornblende, quartz, and a granular mineral having the appearance of zoisite, are the only constituents.

As has been stated before, the diabase structure insensibly shades into the gabbroitic, and even in some of the coarser gabbros the diabasic structure is not wholly absent. In typical cases the feldspar occurs in broad plates, while the augite and hornblende occur more often in the interstitial spaces between the feldspars, as in diabase. They also occur in elongated individuals penetrating the feldspars and penetrated by them in turn. Quartz is commonly present, occupying either angular areas between the feldspars, replacing them, or imbedded in ragged grains in the green decomposition products. Very fine examples occur of a micropegmatitic intergrowth between the quartz and the feldspar, the surface of the feldspar being dotted with similarly oriented quartz grains. The feldspars in some of the slides are perfectly clear, but appear generally more or less granulated. The extinction angles are more easily measured than in the case of the finer-grained rocks. The angle is high, approximating 36°, thus pointing to the presence of a basic labradorite. In many of the slides the augite has been completely changed to green shreddy hornblende dotted with magnetite grains. Where the change is not complete, the augite appears surrounded by hornblende, or granulated with hornblende shreds. A slide from the specimen analyzed contained augite and secondary hornblende in about equal proportions. The augite frequently incloses small crystals of feldspar in a poikilitic manner. In the alteration of augite to hornblende the twinning plane of the former is preserved as the plane of twinning of the hornblende. Zonal extinction is a very common phenomenon of the feldspars in the gabbro. The transition from the more basic core to the acid exterior is abrupt and takes place near the outer boundary. The basic core is marked by the fact that it is often clouded, while the outer rim is always fresh. The subsequent addition has often been much greater on certain faces than on others, so that the form of the core is not pre-

served in the exterior. Apatite is present in some slides. One short, thick rod was noted having OP at one end and a pyramid at the other.

Chemical and Mineralogical Character.—Some interesting features appear in connection with this series of intrusives and flows. One is the mineralogical simplicity of an exceedingly complicated series of eruptions. The only primary components recognizable are: plagioclase, augite, hornblende, apatite, and magnetite. During the petrographic investigation the question arose as to whether all the volcanic flows and related dikes were really basic enough to be termed basalts. The feldspar microlites were so decomposed that measurement was difficult. The angles, however, as nearly as they could be determined, were low in all cases, the highest ranging from 15° to 22°. A sample of one of the dark greenish masses cutting across the spheroidal basalt was taken for analysis, and the result is given in No. II, in the table below. The feldspar in this rock is apparently the same as that in the spheroidal basalt, and the excess of silica and alkalies and lack of lime are quite puzzling. A partial analysis of the spheroidal basalt is also given in No. III. This corresponds more nearly with what would be expected from the microscopic examination. An extreme degree of alteration is shown by all these fine-grained amygdaloidal rocks, which, to a certain extent, invalidates any conclusion which can be drawn from the analysis. Making allowance for this state of things, there is certainly a greater chemical difference in the flows and dikes than was at first supposed. It is probable that none of the rocks contain much less than 50 per cent of silica, and that they range as high as 56, with a proportionate decrease in lime, and increase in alkalies. The most acid facies must be considered as an andesite.

The gabbro taken for analysis (I) is a comparatively fresh rock with both hornblende and augite, but less magnetite than is usually present. The character of the feldspar in the diabasic facies is the same as in the gabbro.

Alteration interferes with the drawing of any exact conclusions in regard to magmatic variation in this series, a variation which it might be expected would be considerable. The order of succession is, as far as was made out, amygdaloidal basaltic flows; less amyg-

daloidal intrusions, in some cases at least, andesitic; gabbro with diabasic facies; dikes in the gabbro; the lavas of the volcanic neck and perhaps dikes of the same age.

ANALYSES OF GABBRO, ANDESITE AND SPHEROIDAL BASALT.

	I.	II.	III.
SiO_2	49.56	55.80	50.56
Al_2O_3	20.09	18.22	....
FeO	2.02	8.98	....
Fe_2O_3	2.32		
CaO	15.62	4.40	6.24
MgO	7.01	2.23	....
Na_2O	1.63	6.34	....
K_2O	.34	1.90	....
Ig	2.25	2.30	....
	100.84	100.17	
Sp. gr.	2.93	2.72	

Volcanic Ash.—A small area of volcanic ash occurs a little above the foot of the grade on Corralitos Creek. The exposures are not good, and its relations to the spheroidal basalt are not revealed. In the hand specimen it appears as a rather soft rock of light color, containing fragments of pumice and dark pebbles. Viewed under crossed nicols it appears to be almost entirely isotropic. There are a few clear grains of feldspar.

GABBRO, PERIDOTITE, AND SERPENTINE.

Field Relations.—The most complicated and, in many respects, the most interesting of all the eruptive masses which are found on Point Sal extends from Point Lospie, three miles in a southeasterly direction. For the first mile and a half it forms a narrow fringe along the coast, and where the latter begins to turn to the south, the eruptive complex passes inland, terminating finally in a low rounded hill, which rises to a hight of 700 feet at the southern foot of a spur of the main ridge.

A detailed description can be perhaps best given by beginning at the western end, and following the coast line, also noting the various sections in the gulches which cross it. For nearly half a

mile southeastward from Point Lospie, the gabbro has a fairly uniform character. It is generally a coarsely crystalline rock with a somewhat varying proportion of feldspar. At the western end it is perfectly massive, but toward the east there appears in places a tendency to the formation of a gneissic structure, which, in connection with a more or less regular banding, finally comes to be the predominant structure. In one or two places, veins or segregated bands of almost pure feldspar appear. Two fine-grained, greenish dikes of ophitic diorite were noted, which are similar to those in the serpentine farther east; also a darker dike, very fine on the edges, and coarser in the center, which a thin section showed contains quartz in addition to feldspar and hornblende. One of these dikes was finely and regularly banded through the arrangement of the ferromagnesian constituents in thin layers. About half a mile from Point Lospie the gabbro begins to show marked variations in composition and structure. The banding or gneissic structure is present in nearly all portions, the bands running in a direction which is usually more nearly east and west than the shore line. A crush zone extends nearly parallel with the shore for several hundred feet. In it the gabbro, with the exception of nodules, has been reduced to a clayey mass and strongly reddened. About half way between Point Lospie and Point Morrito, there begin to appear veins consisting of feldspar, augite, and olivine, rarely hornblende, which are very coarsely crystallized, and extend irregularly in every direction. These vary from an inch to ten inches in width. Their origin is somewhat difficult of explanation, for they do not have the appearance of being dikes. In many cases there is no sharp line of demarkation between the vein and the walls. The granular pyroxene, feldspar, and olivine of the rock interlock with the constituents of the vein without showing any appearance of a break in the period of crystallization. In this vein crystallization has progressed more slowly to the formation of crystals sometimes two inches in diameter. It would seem as if they must be due to the same cause as the veins in the augite-teschenite, that is, to irregular planes through the rock mass in which, owing to movement or tension, crystallization progressed very much more slowly. They correspond in appearance to many so-called "segregated veins;" but in these

cases the constituents are present in the vein in the same proportion as in the rock adjoining. Toward Point Morrito veins of a similar appearance occur in the olivine pyroxene rocks, which can not perhaps be explained the same, because of the lack of feldspar in these rocks; and it is quite possible that they are true dikes.

The banded gabbros are finely exposed at many points on the smooth faces of the cliffs. The gneissic structure is a more constant feature than the banding proper. By gneissic is not meant the structure due to the parallelism of tabular constituents, but that

FIGURE 4.—The banded gabbro.

due to the drawing out of the aggregates of the different constituents, feldspar, augite, and olivine, into irregular, lenticular forms. Rocks showing this structure shade on the one hand into the massive varieties, and on the other into the banded. The facies in which the banding is most apparent to the unaided eye contain an excess of feldspar, which is often drawn out in the most even and regular lines (Fig. 4). Instances were noted in which the feldspar bands one-half inch in thickness appeared as continuous straight lines for ten feet. As a rule the most regular bands of feldspar are

not over a half inch in thickness, but they sometimes reach two inches and more, rarely four or five. In these cases they are almost perfectly pure, while the intermediate bands containing the ferro-magnesian silicates are not pure but contain feldspar in varying proportions. A hand specimen was obtained containing bands of feldspar from one-eighth of an inch to two inches in width.

About 2,000 feet west of Point Morrito an irregular body of serpentine (altered picrite) appears extending parallel to the shore for several hundred feet, cutting off the gabbro in the upper part of

FIGURE 5.—Inclusions of gabbro in serpentine on the contact.

the cliffs from that forming the arms which extend out into the water. Its relation to the gabbro is an interesting one, but difficult to understand. The following sketch from a photograph (Fig. 5) shows the manner in which the gabbro is inclosed in the serpentine. Both are perfectly massive, no appearance of shearing being noticeable in this vicinity. They appear mixed on their edges in the most intricate manner. The stringy and ragged edges of the gabbro, the mutual penetrations and apparent inclusions of one in the other near their line of contact, make it appear as if both were more or less viscous at the time of the intrusion of the picrite. It does not

seem possible that a rigid body could be penetrated as the gabbro has been and yet retain its solid condition. At the spot where the photograph was taken, it seems as if the gabbro must have been the more fluid of the two, but in other places a short distance away the reverse is certainly the case. Although in general the contact is sharp, there is sometimes a slight blending with long narrow arms of the gabbro projecting into the serpentine. One important fact, which would lead to the supposition that the phenomenon is due to an invasion of the gabbro by the picrite is, that almost everywhere near the contact, the latter contains more or less feldspar in aggregates which present to the eye a slight resemblance to poikilitic crystals, often drawn out in rude parallelism. An inclusion of a boulder-like mass of gabbro in the serpentine was noted which has a peculiar character. It is about two feet in diameter, and shows concentric bands of feldspar arranged on three sides near the periphery. The simplest explanation of the inclusions in the serpentine, and probably the true one, is that of absorption of the gabbro by the more magnesian magma. The latter must have retained its heat for some time, and literally eaten into the gabbro, the irregular contact being due to fissures along which resorption would proceed faster.

A body of gabbro and related rocks lying south of the western end of the serpentine, and forming one of the projecting points, offers a most interesting field for the study of many different intrusions of varying character. A part of it consists of gneissoid and finely banded troctolite. In other portions there is a confused mixture of gabbro of different kinds. Patches of a banded gabbro appear inclosed in a somewhat similar rock, whose banding makes an angle with that of the inclusion, the boundaries not being strongly marked, as if a partial fusion of the latter had taken place. Across one end of the area, a dark, fine-grained norite-gabbro has been intruded obliquely to the banding of the larger mass, while along the contact there is a differentiated layer of almost pure feldspar. Dikes are seen which vary in different portions, as well as those which are uniform and distinct. Among the coarsely crystalline rocks the troctolite is prominent. The darker, finer-grained dikes, including gabbros, norite-gabbros with or without olivine, and

picrite, show every variation between the troctolite and the non-feldspathic peridotite. Between this point and the Chute at Point Morrito, the different facies of the feldspathic and non-feldspathic rocks appear in such variety, and show such complex intrusive relations, that it is difficult to give an intelligible description. The serpentinized picrite, which lies between these complex bodies of gabbroitic rocks and the mainland, continues toward the southeast until it narrows and passes into the cliffs. At the last spot where it was observed it forms a dike-like intrusion across the banding of the gabbro, and both are in turn cut by a narrow dike of norite-gabbro. The confused mixture of the serpentine with the gabbro, which has already been described, is characteristic of the contact at different spots. There are many illustrations of the inclusion of the gabbro in the serpentine. It is shown clearly that the gabbro was fully consolidated and subsequently broken up by the basic magma which ate its way in resorbing the solid rock, until it left long arms of nearly isolated or wholly inclosed fragments. During this process little movement seems to have taken place, and since consolidation none at all. Inclusions of gabbro, often several feet long, show the same uniform banding as that adjoining the serpentine. The banding may be parallel to the long diameter of the inclusions, or oblique, and when several fragments appear near together, it is approximately parallel in them all.

The gabbro forming the last rocky projection west of Point Morrito has also a varied character. Much of it is finely banded, the bands extending for many feet in perfectly straight lines. An interesting inclusion of dark hypersthene gabbro, having an elliptical shape, occurs inclosed in a coarser rock of the same character. The bands of the inclosing rock are cut off by the inclusion. A dike of peridotite, cutting the gabbro and gneissoid troctolite, contains inclusions of the adjoining rocks. These vary in size from very small grains up to elliptical masses four inches in diameter, and are so strung along in the dike that it presents a distinctly banded structure. In addition, the dike itself is banded with streaks of a lighter colored feldspathic peridotite. Another dike of serpentine 12 feet wide contains large masses of lighter colored feldspathic material, apparently representing fragments of gabbro partially

absorbed. Their long diameters lie parallel to the walls of the dike. Traversing both the serpentine and gabbro are fine-grained dikes a few inches to a foot wide, which contain feldspar, olivine, hypersthene, augite and magnetite.

Along the western side of Point Morrito the peridotite has been highly differentiated petrographically, and intruded by later dikes, producing a great complication. The cliffs, as far east as the Chute, consist of rock often coarsely crystallized, the predominant component in different spots being either olivine, augite, or hypersthene, with occasionally considerable feldspar. This mass is perhaps 1,000 feet long, and has an irregular outline. It extends to the water, and nearly to the northern side of the complex on the hill above the point; and, although the exposures back from the ocean are poor, it has apparently been forced into the gabbro, terminating on the edges in a series of dikes, and inclosing masses of the gabbro. The relations are the same as those of the serpentinized picrite a little farther west, both bodies undoubtedly belonging to the same intrusive.

This peridotite magma presents great differences in different parts. At the western end it is a dark, compact rock, containing disseminated feldspar, and forming a picrite. In the direction of the main body it becomes coarser, with less feldspar and abundant diallage. Between it and the gabbro occurs a dike of intermediate composition. In the high cliffs at Point Morrito the olivinitic facies is mixed with the pyroxenic in the most confused manner. Over portions of this area the olivine and green diallage appear in about equal proportions, forming wehrlite; in others each component appears segregated by itself to form pure masses of olivine or diallage. These segregations have an irregular form, each extending out in shreddy projections into the other, or the one forming well-defined veins in the other. There is no banding or system in the relation between the two. This interesting condition of things is shown for several hundred feet in the middle and upper portion of the cliffs. On the west side of the Point are the largest areas of almost pure bright green diallage, the crystals reaching one to two inches in length. Where the olivine is abundant, that component has the appearance of forming a paste in which the pyroxene rests, or the

latter penetrates the olivine in veins. Where the pyroxene is in excess, the reverse is the case. In the fresh specimen the olivine is black, but it always appears reddish on weathered surfaces. Towards the water's edge this olivine-pyroxene rock is replaced by a banded feldspathic one, the bands running parallel with the coast, and dipping towards the land. It appears first as dikes in the olivine and pyroxene, while near the water's edge the latter are entirely replaced. The different bands of this more feldspathic magma do not have the appearance of being separate dikes. Although in places the division lines are strongly marked, yet in general there is a more or less blending of the more feldspathic bands into those less feldspathic. These bands might be explained by movement in a heterogeneous magma which rose through the wehrlite before the complete solidification of the latter. At the western end of the wehrlite, where it is the most coarsely crystallized, there is a body of saxonite having a width of at least 40 feet in the upper part of the cliffs. It has an exposed length of several hundred feet, extending up the hill towards the gate in the road. It is generally a dark brownish rock, in which appear large crystals of hypersthene. It blends on the one hand into a facies with no olivine, and on the other into the olivine-pyroxene rocks. On the lower edge of this area there is a segregated mass of hypersthene and feldspar, which, with perfect correctness, might be called norite. A varying amount of feldspar is characteristic of the whole hypersthene area. A vein similar in manner of formation to those in the gabbro traverses the feldspar-hypersthene rock. It consists of those two components in large crystals, the hypersthene reaching a diameter of one to one and a half inches. No sharp lines could be drawn between the picrite on the west and the wehrlite, saxonite, and pyroxenite on the east. The hypersthene replaces more or less completely the augite of the picrite to form the saxonite, but is always associated with some feldspar. The small area of hypersthene feldspar rock is inclosed on all sides by the peridotite, and must be looked upon as a segregation from the magma. Dikes and veins of every conceivable variation between the olivine rock and the feldspathic ones, penetrate this complex between Point Morrito and the gabbro on the west. Many of these are banded and some are coarsely crystallized,

like those in the gabbro. The character of the rock through which the so-called veins pass, has no effect upon their mineralogical composition. It is very difficult to tell which are true dikes and which are veins of segregation. In this vicinity are the most striking and sudden changes in texture, structure, and composition. Portions of the same eruptive mass show as great variations in a very short distance as might be expected from wholly distinct masses.

The wehrlite passes up the hill back of Point Morrito, constituting much of that promontory, but the outcrops are poor. South of the hill and along the coast east of the Chute the formation changes considerably. The wehrlite is replaced by a dark aphanitic serpentine (dunite), which is traversed by many branching irregular dikes of diabase.

The first cañon east of the Chute gives a clean section across the complex, which is here about 1,000 feet wide. The upper portion consists of gabbro for several hundred feet, with a small amount of diabase. There seem to be different intrusions here, but their relations are not plain. Below these is a belt of altered dunite extending to the ocean. It has a uniform appearance, except near the sea, where it contains a small amount of feldspar and enstatite. Just above the water it is intersected by many narrow dikes of diabasic character, and at one spot by a dike of wehrlite. East of the spot where this gulch enters the ocean, a prominent dike of diabase runs parallel with the cliffs for a quarter of a mile. The clean cut contacts with the serpentine show that it is intrusive, a fact which is also corroborated by the character of the dike. It is fine and almost porcelain-like on the edges and coarser in the middle. It adheres so firmly to the serpentine that, instead of parting at the real junction, the separation is about two inches within the serpentine. In addition to the large dike, which is frequently 12 feet in diameter, there are numerous smaller ones. The serpentine here is generally massive, showing lamination only in spots. The exceedingly irregular and bunchy nature of these dikes explains how it is that when shearing has affected the serpentine, the dikes are broken up into boulder-like masses, which, in the most of the serpentine areas in the Coast Ranges, are so difficult of explanation.

In addition to the dikes which are of later date than the serpentine, there appear at numerous spots along the ocean bands and streaks of lighter color. They differ from the serpentine in containing augite and feldspar in addition to olivine, and might be termed picrites, although some are almost gabbroitic in appearance. They are not generally sharply differentiated from the serpentine, the dark bands passing into it with apparently little change. These feldspathic bands are sometimes intersected by dikes, two to three inches in thickness, which do not differ greatly in appearance but contain abundant hypersthene.

The steep southern slope of the Lion's Head consists of a rock quite similar to that forming the higher part of Point Morrito, namely, diallage and olivine, the former frequently in large green crystals. The section given along the first creek east of the Lion's Head is quite similar to that west. On the northern side of the complex there is first 500 to 600 feet of diabase and gabbro. The extreme edge is a dark, fine-grained diabase, containing coarse, irregular veins. The veins recur occasionally until the bridge is reached at the mouth of the cañon, where a dark, aphanitic serpentine replaces all the feldspathic rock. In the serpentine near the contact are bodies of coarse hornblende gabbro, while narrow dikes of serpentine intrude the feldspathic rock. Toward the southern edge the serpentine becomes coarser, with prominent pyroxene crystals. A little above the beach there appears in it, as shown in the sides of a shallow ravine, a broken dike of gabbro. The serpentine near it is greatly sheared, while the banding of the gabbro is apparently diagonal to the course of the dike.

From a point opposite the Lion's Head the serpentines extend only a half mile southward before disappearing beneath the Miocene. The different rock types which appear here are numerous and interesting. Beneath the Head where the road comes nearest to the cliffs there are some irregular dikes of diabase, which have broken through the serpentine and caught up fragments of it as shown in the annexed sketch, taken from a photograph (Fig. 6). The cliff section cuts diagonally across the serpentine to its southern side. Following along the shore, from the point where the large dike occurs, there are many small ones to be seen. These split up into

branches two to three inches in thickness, from which branch again still smaller ones perpendicularly, thinning out finally to knife edges. The large dikes and many of the smaller ones contain inclusions of serpentine. These inclusions are frequently

FIGURE 6.—Irregular dike of diabase inclosing fragments of serpentine.

drawn out in long, shreddy wisps. In order for these to assume the form shown here, it would seem necessary for the serpentine to have been in a somewhat plastic condition. Occasional dikes of hornblende gabbro contain rounded and partially absorbed nodules of serpentine. In one instance these inclusions appeared surrounded by a green border shading into the gabbro. In one case the inclusions of serpentine in a gabbro dike are sharply angular in outline (Fig. 7). The dark serpentine which forms the most of the coast line from the Chute southeastward is interseeted in many places by veins one to two inches wide. These consist either of feldspar and coarse crystals of green pyroxene or wholly of pyroxene. In the

FIGURE 7.—In the center are shown angular fragments of serpentine inclosed in a gabbro dike.

vicinity of the greatest development of the diabase dikes considerable movement has taken place, and veins of pectolite fill the seams. They are most abundant in the diabase and along the contact. South of the Head a dike of olivine-rich gabbro occurs in the serpentine. Near the southern end of the cliffs there is an interesting series of gabbroitic dikes. The following section is shown: First a gabbro dike 200 to 300 feet wide, then a few feet of dark, sheared serpentine containing nodular masses of a hypersthene gabbro, probably a dike broken up by movement; after this an irregular dike of gabbro two to five feet wide, followed by another of picrite, and that by a dike of troctolite; serpentine at last terminates the series, disappearing beneath the débris. At several spots there were noted dikes intermediate in character between the gabbros and peridotites, which were later than the peridotite, but there are good examples of distinctly gabbroitic dikes intrusive in the dunite.

The last and deepest of the cañons which have been eroded across this eruptive complex is that leading up to the dairy and the old gypsum mines. A section is shown here quite similar to that farther west. At the northern side there are diabasic dikes of dif-

ferent degrees of coarseness, and a small amount of gabbro and hypersthene gabbro. Below this the dark serpentine extends until covered by the Miocene. Towards the southeast the belt widens to nearly a quarter of a mile. This portion is comparatively simple; for, although there are deep cuts to expose the rock, the greater portion consists of the compact altered dunite, with a comparatively narrow strip, perhaps less than 200 feet, of fine-grained diabase. But little signs of shearing are seen in this portion. This, the largest body of altered peridotite, judging from its massive character, does not bear out the view that is frequently advanced that hydration is the cause of the broken, laminated, or clayey character of many serpentines. Wherever the Point Sal serpentines have lost their massive character, it seems to be due in great measure, if not entirely, to shearing brought about by earth movements. The most disturbed portion is along the coast where it has been intruded by dikes which are generally nearly parallel to the long diameter of the eruptive mass as a whole. This direction corresponds to the lines of movement and faulting in the Coast Ranges.

Microscopic Petrography.—In the field the gabbros are generally distinctly marked off from the peridotites, although there are facies of each almost identical, besides independent bodies of intermediate composition. The following classification is made purely for the purposes of description, and is not meant to convey the impression that there are any distinct types clearly set off from the rest. In fact, there are all conceivable mineralogical transitions between that consisting almost wholly of feldspar and the magnesian or olivine rock. Three main divisions may be made: (I) The olivine-free feldspathic rocks, (II) the olivine-bearing feldspathic rocks, (III) peridotite and pyroxenite.

I.

Feldspar.	Anorthosite.
Feldspar, hornblende.	Hornblende diabase.
Feldspar, hornblende, quartz.	Ophitic quartz diorite.
Feldspar, hornblende, hypersthene.	Hypersthene diabase.
Feldspar, augite (with or without hornblende).	Diabase or gabbro.
Feldspar, augite, hypersthene (with or without hornblende).	Norite-gabbro.
Feldspar, hypersthene.	Norite.

II.

Feldspar, olivine, augite (with or without hornblende).	Olivine gabbro.
Feldspar, olivine, augite, hypersthene (with or without hornblende).	Olivine norite-gabbro.
Feldspar, olivine, hypersthene.	Olivine norite.
Feldspar, olivine.	Troctolite.

III.

Olivine, diallage, hypersthene, little feldspar.	Feldspathic lherzolite.
Olivine, diallage, hornblende, little feldspar.	Hornblende picrite.
Olivine, hypersthene, little feldspar.	Feldspathic saxonite.
Olivine, augite or diallage, little feldspar.	Picrite.
Olivine, enstatite, diallage.	Lherzolite.
Olivine, hornblende.	
Olivine, diallage.	Wherlite.
Olivine.	Dunite.
Diallage.	Pyroxenite.

The feldspar of these rocks, with rare exceptions, all belongs to anorthite. One exception is that of feldspar intergrown with quartz in veins in the serpentine which seems to lie between labradorite and albite. Feldspar approximating labradorite is found in several of the diabasic dikes, but in all the facies of the gabbro it undoubtedly belongs at the extreme basic end of the series. Large extinction angles were noted, while the specific gravity ranges between 2.73 and 2.758. It is generally very fresh and free from inclusions. In the rocks rich in olivine, alteration has begun, and where the feldspar forms but a small portion of the rock, as in certain facies of the peridotites, it is completely altered to a white, opaque, and completely amorphous substance. In none of the specimens did apatite appear as inclusions, either in the feldspar or any other of the components. Twinning was noted in the feldspars on the carlsbad, albite, and pericline laws, that of the albite prevailing.

The monoclinic pyroxene has a uniform character, aside from secondary changes, in all parts of the eruptive mass. In the hand specimen it appears a deep green color, but in thin section under the microscope it is non-pleochroic and almost colorless. In many

portions it is exceedingly fresh, but in the coarser rocks and peridotites it shows all stages of the alteration to diallage. The alteration begins by the creation through the center of the crystal of fine cleavage planes parallel to the orthopinacoid. Associated with these parallel cracks in the center of the crystal are long rectangular or spindle-shaped alteration products, which polarize brightly when the remainder of the crystal is dark. Slender magnetite rods are sometimes developed in the alteration. Inclusions of hornblende are quite common, being arranged either irregularly or along the cleavage planes. Occasionally the augite shows an approximation to an idiomorphic form, but in general it is allotriomorphic.

The rhombic pyroxene present is chiefly hypersthene, a colorless non-pleochroic enstatite being seen in only a few instances. The hypersthene is remarkably widespread, occurring in nearly all facies of the rock except some of the purely non-feldspathic ones. Its presence seems to have no relation to the presence or absence of olivine. It is strongly pleochroic, showing the usual colors, $\mathfrak{a}$ = red, $\mathfrak{b}$ = yellow, $\mathfrak{c}$ = green. Sections parallel to the macropinacoid are often devoid of pleochroism, remaining green in all positions, and show the emergence of an optic axis. The axial angle is small, for both axes appear in the field in convergent light. The specific gravity, which is 3.315, is rather low for this mineral, and shows that it is not rich in iron. As a rule the crystals are exceedingly fresh and free from inclusions, which are so characteristic of hypersthene. No schillerization was seen, but in those individuals which had become slightly affected by alteration there has been produced a system of fine parallel cracks.

Hornblende is fully as widely distributed through the different facies of the rock as hypersthene, save that it is less common in the peridotites. It generally plays a less important rôle than the hypersthene, except in the ophite diorites. In the dikes of diabasic structure it has clearly replaced the pyroxene in some cases, while in others it must be considered primary. In the gabbros it sometimes occurs in independent individuals, but more commonly as broken or discontinuous rims about the augite grains, and occasionally about the olivine. It is quite strongly pleochroic, giving brownish, greenish brown, and pale yellow tints. It is what is termed basaltic hornblende.

Olivine is almost universally present in the gabbros and peridotites, but generally absent from the diabasic dikes. It is in a fairly fresh condition in the feldspathic rocks, but appears in all stages of alteration in the peridotites, until the extreme is reached in the dunites, where in some cases its former presence is recognized only by the mesh structure. It never possesses idiomorphic boundaries, but has the form of rounded grains or irregular aggregates of individuals differently oriented.

The rocks as a whole are remarkable for the small amount of iron ores present. Magnetite is absent from the normal gabbro and peridotite, and occurs in abundance only in the narrow dikes which appear to have been among the latest of the intrusions. The peridotites are remarkable also for their small amount of chromite and picotite. In one slide only do there appear a few reddish grains, which are probably referable to one of these minerals.

Having given now an outline of the characters of the rock-forming minerals, a brief description will be added of the various rock facies. The blending of one variety into another adds to the complexity of the subject, but typical examples of the different facies already given will aid in understanding them.

The anorthosites, those rocks poor in the ferro-magnesian silicates, occur in the gabbro in the form of bands occasionally reaching a width of six inches. Bands one to two feet wide, which appear more like veins, occur in the massive gabbro. There are also ill-defined areas in which the dark silicates are sparingly represented. In different parts of this facies appear small amounts of olivine, augite, and brown hornblende. In one vein the feldspars appear most curiously dovetailed into each other, and many individuals, particularly those not showing twinning, present a sort of zonal structure with a jagged outer rim extinguishing at a different angle from a similarly jagged interior.

The dikes possessing an ophitic structure range from true diabases to quartz-diorite. A dike of the latter was noted intrusive in the gabbro. It is four feet wide, dark, and very fine grained on the edges. Judging from the extinction angles, the feldspars evidently belong in the more acid portion of the labradorite series. They have well-marked zonal structure. The hornblende is without any

doubt primary, showing characteristic basal sections and a pale greenish brown color. Quartz occurs filling interstices between the other components, being the last to separate. Magnetite is quite abundant in skeleton crystals.

The question arises in regard to the proper designation for a rock of this kind. A silica determination gave 66 per cent, which is rather acid, even for a diorite, as the term is used. The distinction which Brögger* has proposed seems a very good one, that is, to confine the use of the term diorite to the medium acid abyssal rocks of granitic structure, while the term diabase is to be used for the hypabyssal rocks. These to be farther divided into medium and basic rocks corresponding to the deep-seated ones diorite and gabbro. He considers the classification according to the ruling dark constituent of very little value.

In accordance with this the rock will be designated simply an ophitic quartz-diorite. A new name, it would seem, must ultimately be adopted for medium acid rocks of diabasic structure.

Another dike farther east contains greenish brown hornblende in granules and broad plates. The latter are thickly dotted in a poikilitic manner with exceedingly minute feldspar laths. The greater number of the diabase dikes east of the Lion's Head contain a greenish, shreddy hornblende and lath feldspars. The former often incloses cores of granular augite, showing that a part of the hornblende at least has been derived from augite. The primary nature of a part of the hornblende is evident from the form of the basal sections and the manner in which it incloses the feldspars, a similar structure not having been seen in the case of the augite. As a general thing, the feldspar of these rocks is more decomposed than in any of the other feldspathic rocks.

A rather interesting dike of diabase occurs intrusive in the serpentine south of the Head. It is a fine-grained rock, containing poikilitic crystals of primary brown hornblende. In these crystals are numerous inclusions of feldspar, augite, and hypersthene. The hornblende and augite are slightly more abundant than the hypersthene. The feldspar laths probably belong to anorthite. Small

* Die Eruptionsfolge der Triadischen Eruptivegesteine in Südtyrol.

grains of magnetite are abundant. All the minerals of the rock are fresh. There are a few large crystals of augite showing the diallagic cleavage.

A fine-grained dike, three inches wide, is intrusive in the gabbro and peridotite west of Point Morrito. A thin section shows hornblende, augite, hypersthene, and feldspar, the minerals all being in a fresh condition. A distinct banding is shown, due to the segregation of a part of the hornblende. The four constituents are present in about equal proportion, while magnetite is abundantly scattered through the rock. Although the most of the constituents are granular, there is a tendency to the elongation of some of the feldspars and their arrangement with their long diameters parallel to the walls of the dike. No other instance of a parallelism of this kind appeared.

In a dike of crushed serpentine south of the Head occur nodules of a dark, fine-grained rock, with serpentine adhering to one side. They appear to belong to a dike broken up in the movement which brought about the crushing of the serpentine. The composition of this rock is the same as the last. There is a slight tendency toward the arrangement of the constituents in lines. This is particularly noticeable in the case of the magnetite, which appears in bands made up of scattered grains.

The combination of minerals just described is not a common one for the coarse gabbro, olivine being so widely distributed through that rock that but few specimens were obtained which did not contain it. The combination of feldspar and augite or diallage is also uncommon in the coarser rocks.

Norite-gabbros are not abundant, though several dikes of this rock occur. Hornblende almost always is present in these dikes, which are most numerous in the gabbro-peridotite area west of Point Morrito. A small dike only a few inches wide, and almost aphanitic in the hand specimen, might be cited as a characteristic example. Under the microscope it is seen to possess a typically holocrystalline granular structure. The components, feldspar, augite, and hypersthene, are perfectly fresh and present in about equal proportions. Magnetite dust is scattered thickly through the slide.

The typical norite, free from augite, was found to occur only as

a facies of the complex peridotite area at Point Morrito. Here is a small body of rock, a segregation from the magnesian magma which surrounds it on all sides. It consists of feldspar and hypersthene in varying proportions, and, occasionally, small grains of magnetite. The constituents are fresh and free from interpositions. With decrease of feldspar there are transitions to a rock consisting almost wholly of hypersthene, and with the addition of augite and olivine gradations to the more common peridotite. A portion of this norite is very coarsely crystallized, the crystals reaching a diameter of one and a half inches.

The typical olivine-gabbro is an abundant rock, and is represented in the collection by many slides. It often contains a little hypersthene and shreds of brown hornblende. The olivine occurs in irregular-shaped aggregates, and in those rocks which are banded it is strung out in more or less connected patches. The beginning of alteration is usually apparent in a yellowish border and an intersecting network of cracks. Although the first mineral to separate out, it is never idiomorphic. A number of inclusions of olivine in augite were observed where the grains of the former had a very perfect elliptical outline. One of the most striking phenomena associated with these olivine-bearing rocks is the system of radiating cracks which extend out into the feldspar from the olivine aggregates. These cracks are grouped in parallel or radial bunches, diverging from the projecting points of the olivine aggregate and extending through the intervening feldspar, to the adjoining aggregates of the same mineral. The extent to which this is developed, even in those rocks in which alteration is but slightly apparent in the olivine, is very remarkable.

In the coarser rocks, and in the larger individuals of augite in most specimens, there is observed the beginning of alteration indicated by the development of an assemblage of fine parallel cleavage cracks and polarizing interpositions. In the banded varieties, the olivine is segregated in layers; other layers consist of olivine and augite, between which are the feldspathic bands, containing some augite, but free from olivine. The fresh condition of the augite, which in many sections has associated with it partial rims or shreds of brown hornblende, make it fairly certain that the latter is original, and was the last constituent to crystallize out.

With the decrease of augite we reach the type of rock to which he term "troctolite" has been given (German, Forellenstein). This rock sometimes occurs as facies of the normal gabbro, and sometimes as homogeneous independent dikes. A dike of this kind appears intrusive in the serpentine south of the Lion's Head. The greater portion of the troctolite is found in the near vicinity of the peridotite area west of Point Morrito. While it occurs here well-defined from the true gabbros, yet it is genetically connected with them rather than with the peridotite. The rock is here remarkably gneissoid, owing to the arrangement of the olivine granules in long, platy aggregates. It is an interesting fact that the olivine grains never occur alone, except as inclusions in the other constituents. The feldspars are invariably allotriomorphic. The rocks are rarely free from small amounts of augite and hornblende. Magnetite is absent from all the specimens examined.

Olivine norite gabbro is quite common, occurring almost always as dikes in the complicated area west of Point Morrito. Some of these have a subordinate amount of feldspar, and might perhaps be considered as transitions to the peridotite. South of the Lion's Head a dike of this composition was seen intrusive in a peridotitic rock. The latter consists of augite, olivine, feldspar, and hornblende, the two last components in small amount, while magnetite is abundant. The dike is about two inches wide, but possesses a typical granular structure with the following composition: augite, hypersthene, feldspar, olivine, and a small amount of magnetite. The constituents of the two rocks interlock along the contact in such a manner as to lead to the view that the older was not fully consolidated at the time of intrusion.

A hornblende-bearing facies of this type is illustrated by an interesting specimen from the cañon below the dairy. It is somewhat more coarsely crystalline than the others, and contains an abundance of granules and irregular plates of a pale yellowish brown hornblende with weak pleochroism. It is intergrown in several cases in a granophyric manner with the augite. Some of the hornblende has a poikilitic habit, with inclusions of the other constituents. Several large irregular crystals of olivine are present, and one section of twinned augite approximately idiomorphic. There is in addition a very little magnetite.

Observation both in the field and with the microscope confirms the fact of a continuous petrographic series between the strictly feldspathic and the non-feldspathic portions. Feldspar is widely distributed in rocks which must really be classed with the peridotites under our present nomenclature. As an example of this may be cited a rock consisting of olivine, hypersthene, and feldspar. The olivine forms about half of the rock, while the remainder is equally divided between the other two. The olivine is largely decomposed to a reddish brown mesh with fresh cores, while the comparatively fresh feldspar is distributed through it in small crystals. The hypersthene occurs in relatively large, almost porphyritic individuals, also quite fresh and free from interpositions.

An examination of the literature upon serpentines and peridotites shows that much confusion exists. The usage is so different by different authors that it becomes very difficult to reduce to any system of classification the great variety of these rocks in the area under consideration. Much of the peridotite is quite fresh, the greatest amount of alteration of course being confined to that richest in olivine. The augite may be either normal or show all stages of change to diallage, the larger crystals being generally diallagic, while the smaller are normal augite. As many authors have based the classification on the character of the monoclinic pyroxene, whether augite or diallage, it adds much to the difficulty of making a classification which shall conform to usage.

Under the head of lherzolite are grouped those rocks which contain olivine, augite or diallage, hypersthene or enstatite, and often a small amount of feldspar. These rocks are chiefly confined to Point Morrito, where they are intimately associated with non-feldspathic peridotites. Except for the occasional patches of feldspar, hypersthene is the most striking constituent in the hand specimen, appearing in porphyritic crystals one-fourth to one-half inch in diameter, imbedded in a base of olivine and minute feldspars. Under the microscope the olivine appears to have decomposed to an almost opaque network of magnetite and reddish oxides, scattered through which are fresh olivine cores. The feldspar is comparatively fresh but seamed. The larger individuals of hypersthene show no crystal boundaries, but are fresh, and without interposi-

tions. The pleochroism is rather weak. Crystals of diallage are occasionally present. Some sections contain no diallage, and might be termed saxonite. Intimately related geologically to the hypersthene peridotite is a large area consisting of diallage and olivine with or without feldspar. Where the olivine is greatly in excess, and much decomposed, the feldspar has been changed to a white, translucent but isotropic substance. In some facies in which the diallage is in excess, the olivine forms a sort of cementing paste in which it is imbedded. The pyroxenes show no true crystal outlines; yet there is often a rude approximation to them. With an increase of olivine there is an increased amount of alteration noticeable, the olivine being reduced to a brownish serpentine, with here and there fresh cores. The pyroxenes appear fissured and permeated with seams of serpentine.

An interesting section was obtained from the southern slope of the Lion's Head. It consists of partly serpentinized olivine and diallage in nearly equal proportions. The apparently separate individuals of the latter are almost similarly oriented, as shown by the extinction angles. An examination of the hand specimen showed the existence of lustrous mottled surfaces an inch or more in diameter. This indicates that the extinction phenomenon is produced by large poikilitic crystals of diallage. The slight discordance in orientation appearing in the section may be accounted for by strain and movement brought about by the hydration of the olivine matrix.

It is rather difficult to distinguish the wehrlites from the picrites unless the feldspar present in the latter be made the basis. The fine-grained peridotites west of Point Morrito containing feldspar are not clearly set off from the wehrlites through any peculiarity of the pyroxene. In the picrites proper the pyroxenic constituent is supposed to be augite, but in the rocks mentioned it is more nearly diallage than augite, the smaller individuals still retaining their augitic character, while the larger are undoubtedly diallage. Thin sections of these rocks show the olivine to be in an advanced stage of alteration. It is represented by an almost colorless or grayish aggregate of felted serpentine shreds, among which appear occasionally grains of altered feldspar (isotropic) and a pale colored augite or diallage.

The lherzolite type with enstatite as the rhombic pyroxene is rather sparingly represented. A thin section from the dark serpentine east of the Chute contained a serpentinized olivine in excess, with here and there irregular grains of a colorless rhombic pyroxene, and still more rarely those of a monoclinic pyroxene. Another specimen obtained near the Lion's Head contained, in addition to the minerals in the last, allotriomorphic masses of reddish brown hornblende. The latter appears to be the freshest of any of the constituents.

The pyroxenite occurs at Point Morrito as segregations in the wherlite. It is seldom wholly free from olivine, and occurs in irregular patches of considerable size imbedded in a matrix consisting chiefly of olivine.

The dunite is represented by the dark homogeneous serpentine. It forms by far the larger part of the peridotite area, being mainly developed between the Chute and the eastern end of the complex. Under the microscope its derivation from olivine appears clear. In specimens in which the alteration is not complete there are scattered spots of small size of a brilliantly polarizing, highly refracting mineral. These grains are inclosed in a mesh of interlacing fibers of serpentine. Numbers of them near together extinguish simultaneously, showing them to be portions of a single crystal. With the analyzer removed the reticulated mesh structure, which is considered characteristic of olivine, is apparent throughout the whole slide with the exception of the clear spots. In some slides no olivine remains.

A remarkably banded rock occurs near the Head. This contains hornblende, augite, olivine, hypersthene, and feldspar. Owing to the small proportion of feldspar it might be considered as belonging between the two main groups. The large irregular plates of yellowish brown hornblende contain inclusions of all the other constituents. The diallagic augite is gathered in bands free from the other components, the individuals being arranged with their vertical axes approximately normal to the edges of the band.

The petrography of the "segregated veins" or dikes which appear in different portions is interesting. Without doubt these occurrences can be divided into two classes, one of which might be

termed contemporaneous segregations, which, on account of a prolonged period of solidification, took on their coarsely crystalline character, and the other true dikes of later age than the rocks which they intersect. It is not always possible, however, to draw the line between them. The segregated veins in the gabbro do not differ much, or even any, from the average composition of that rock. They consist of feldspar, diallage, and olivine. The two former in large individuals, the last in aggregates of grains as in the normal rock. Veins of essentially the same composition appear also in the peridotite, but in the hypersthene area there are very coarse vein-like masses of hypersthene and feldspar which do not appear elsewhere.

Veins with black hornblende appear at one spot west of Point Morrito. It is associated with feldspar and augite. The augite in a pure granular aggregate forms the outer portion of the vein, while in the center are feldspar and large crystals of hornblende. A fragment in which the cleavage was well developed was examined with a goniometer and the angle found to be the same as that of normal hornblende, namely, 124° 30′.

The altered dunite and related rocks east of the Chute are intersected by many slender veins contrasting strongly in color. They consist of diallage and a white substance which under the microscope is generally completely isotropic. From its close resemblance to the feldspars of the olivine rich rocks which are undergoing a change to a similar cloudy milky substance, it is believed that it belongs among the feldspars. The veins vary in width from half an inch to two inches. In the narrower ones the pale green diallage is confined to the outer edge. The crystals seem to be planted on the walls and to have grown inwards. The center consists wholly of the dull feldspar. In the wider veins the pyroxene is not confined to the edge, but is scattered throughout indiscriminately.

At the foot of the cliffs south of the Lion's Head some large pieces of serpentine were found which are cut by white dikes or veins four to five inches wide. The substance of which they are composed is fresh and clear, and contains long, slender, brownish crystals sparingly disseminated along the edges. The walls of the dike are clean cut, with no transition to serpentine. Slides prepared

from the center and edges showed an interesting association of minerals. The white mineral from the center resembles feldspar, but shows no twinning, and is intergrown in a micropegmatitic manner with quartz. The angle of extinction of the supposed feldspar measured on a cleavage crack is very low. The section prepared from the edge showed only a small amount of quartz intergrown as described, but numerous lath-shaped feldspars twinned according to the albite law. Owing to alteration the extinction angles were difficult to measure, but those obtained indicated that it belonged between albite and labradorite. In portions of the slide the feldspar was observed undergoing alteration to the same cloudy isotropic substance already described. The slender crystals observed in the hand specimen proved to be a pale, slightly pleochroic hornblende. This was shown by the extinction angle of twinned individuals, which is 18°, and by characteristically shaped cross sections with the usual cleavage. The pale color of the hornblende, taken together with its specific gravity, which was found to be 3.065, indicates that it is a variety intermediate between tremolite and ordinary hornblende, a hornblende poor in iron. In other sections of similar occurrence many of the individuals appeared perfectly colorless, and are undoubtedly closely allied to tremolite. The specific gravity of the granophyric intergrowth was found to be 2.654.

In the case of another dike, a layer of brown hornblende forms the edge, lying between the feldspar and the serpentine, though sometimes separated from the latter by a thin sheet of feldspar.

Turner* has described veins in serpentine from Meadow Valley in the Sierra Nevada. The feldspar was proved to be albite by analysis. Similar veins have also been seen by the author in the serpentines in other places in the Coast Ranges.

Age.—The field relations give no clue to the exact age of these rocks. They are older than the Miocene, but beyond that we can go only by their analogy with similar eruptives in this part of the Coast Ranges. In the San Rafael Mountains, 40 miles to the southeast, there is a large body of serpentine having associated with it dikes of diabase. The whole has been intruded into rocks of sup-

* American Geologist, Vol. XIII, p. 303.

posed Knoxville age. About the same distance to the north, in the vicinity of San Luis Obispo, are other large bodies of altered peridotite, also intrusive in the Knoxville. As far as is known no eruptives of this kind have been intruded in the Chico. The Point Sal occurrence differs from all others known in the Coast Ranges in regard to the large amount of gabbro accompanying it. Large areas of olivine and norite-gabbros have been found by the author in the Peninsular range in the southern part of the state, but there is no means of correlating them with the similar rocks at Point Sal. It seems more than probable that the rocks under discussion are differentiated portions of the same basic magma which invaded the Coast Ranges through their whole length at some time between the deposition of the upper and lower Cretaceous.

Comparison with Other Peridotites of the State.—Peridotites are among the most widely distributed of the eruptive rocks of California. They occur through the Coast Ranges from a point a few miles southeast of Point Sal northwest to Oregon. They are met with along the western slope of the Sierra Nevada from Mariposa County north until covered by the lavas. It is a well-known fact that until recently geologists who have worked in California have considered the serpentine of sedimentary origin. M. E. Wadsworth,* who investigated some of the material collected by the old State Geological Survey, is an exception, for all the specimens which came under his observation he believed to be of eruptive origin. In 1891, H. W. Turner † showed that the serpentines of Mt. Diablo are altered eruptives, and expressed the opinion that there is a genetic relation between the peridotite and the gabbro found there. In a paper published in 1892 the author ‡ advanced the opinion, based on an examination of parts of the Coast Ranges, that the serpentines are all altered eruptives. Later Dr. Palache‖ described the serpentine, and associated rocks of the Potrero, San Francisco. There he found a lherzolite generally sheared in an extreme degree, and accompanied by lenses of fine-grained rock

* Lithological Studies.

† Bull. Geol. Soc. of Am., Vol. II, p. 389.

‡ Am. Geol., Vol. IX, p. 153. Eleventh Report of State Min. of Calif.

‖ Bull. Dept. Geol. Univ. Cal., Vol. I, pp. 161–179.

which proved to be hypersthene diabase and epidiorite. These lenses were believed to be portions of a dike intrusive in the serpentine and broken up by a subsequent movement. F. L. Ransome* has described the serpentine of Angel Island, and shown that it originally consisted mostly of diallage. Inclusions occur here also, but their nature and position are such that the conclusion was reached that they could not be intrusions but fragments of an adjoining rock enveloped in the magma.

Observation has shown it to be a fact that nearly all the numerous bodies of serpentine have associated with them smaller masses of feldspathic rock which vary in character from gabbro to diabase. The relation of these feldspathic rocks to the peridotitic has been very difficult to determine with certainty. This is due partly to poor exposures, and partly, perhaps chiefly, to the frequently disturbed condition of the altered peridotites. Many of the largest areas, namely, those at New Idria and Knoxville, have undergone internal stress and shearing on an extensive scale, and as a result have been reduced to shaly or even pulverent masses. Scattered through these crushed areas are nodules of massive serpentine, and lenses of a gabbroitic or diabasic character. These occur in a manner similar to that described by Dr. Palache. The author † has noticed and described the same condition of things existing on a large scale near Knoxville, Lake County. Not only do there occur here lenticular inclusions of what are without doubt foreign bodies caught up in the magma, but also lenses of fine granular crystalline rocks whose relations are puzzling. There are places, however, where these lenses are clearly shown to be portions of disrupted dikes, and it is probable that such is the character of the larger part of similar occurrences.

The dikes of diabase on the southern side of the Lion's Head are very irregular, swelling out and then almost pinching. Should movement take place along the sides of such a dike, it would be broken up, and the fragments separated from each other would present an appearance closely resembling foreign inclusions. Incipient stages of this kind appear in the cliffs. In one case a compar-

* Bull. Dept. Geol. Univ. Cal., Vol. I, p. 219.

† Eleventh Report of the State Min. of Cal., pp. 69–71.

atively narrow mass of serpentine between two gabbro dikes, offering the least resistance to crushing, has been reduced to clay, and contains nodules of a dike not seen in place in that vicinity.

Relation between the Magnesian and the Feldspathic Rocks.— The study of the rocks at Point Sal, taken together with what is known of similar areas in other parts of the state, leads irresistibly to the conclusion that there is a genetic relation between the feldspathic and non-feldspathic types. It appears also that there is a common sequence for at least some varieties of the rocks thus associated together. The Point Sal occurrence differs chiefly from others in the state in the great variety of rocks, as well as in the presence of a comparatively large area of gabbro.

The association of gabbro and peridotite is a very common one in other parts of the world. G. H. Williams* says: "Olivine rocks and serpentines are more or less extensively associated with most of the large gabbro areas which have hitherto been carefully studied and described (*e. g.*, Hartz Mountains, Saxony, Lower Austria, Scandinavia, etc.); and the Baltimore region proves to be no exception to this rule." In the first of his papers on the rocks of the Cortland Series,† he says, after giving the classification of Professor Dana, diorite, norite, diabase, gabbro, and peridotite: "This classification may perhaps be advantageously followed, provided it be remembered that no sharp line can be drawn between the different groups, but on the contrary every possible transition from each group into every other occurs." Bailey‡ has described basic peridotitic separations from the gabbros of the Lake Superior region, but they are local and belong to the same period of eruption. Judd§ says of the gabbros and peridotites of Scotland: "Locally both gabbros and dolerites are found passing into peridotites by the gradual disappearance of the feldspar and the increase in the quantity of olivine." He says also that segregation nodules of gabbro are found in the peridotites, and *vice versa*, and also that "the so-called 'segregation veins' of peridotite are seen traversing the

*U. S. Geol. Survey Bull. 28.

†American Jour. of Science, Vol. 31, p. 27.

‡Journal of Geology, Vol. II, p. 817.

§Quart. Jour. of the Geol. Soc., Vol. XLI, pp. 358, 359.

gabbro, and similar veins of gabbro are found intersecting the peridotite masses. The relations of the gabbros and peridotites in the Western Isles of Scotland seem to indicate that, in the heart of these old volcanoes, the feldspar, olivine, and augite tended to segregate in certain cases into masses of various dimensions, and that these masses were, after consolidation, fissured again and again, the fissures being injected by different portions of the magma, which were still in a more or less plastic condition." Bonney,* in describing an area of troctolite and serpentine in Aberdeenshire, says that the feldspathic rock is the later. He quotes Judd as observing a sequence of serpentine, troctolite, and gabbro. In notes on some Ligurian and Tuscan serpentines he† describes the occurrence of serpentine and gabbro together in a number of places and expresses the opinion that it can hardly be a coincidence. Bonney‡ also notes, in describing the serpentines of Ayrshire, dikes of diallage rock cutting serpentine, and gabbro cutting both in turn.

From these references it will be seen that the association of feldspathic and magnesian rocks with intermediate types is a common one. There must certainly be a genetic relation, as suggested by several writers. There can be no question that at Point Sal all the extreme variations and successive intrusions had one common parent magma.

The Banded Structure.—The remarkable banded and gneissic structures shown in many portions of these rocks are among their most interesting and peculiar features. Although the banding is of course absent from the large area of altered dunite and from a portion of the gabbro at the western end, yet it is such a common phenomenon in almost all facies of the mass, that it deserves a careful description. Two fairly distinct divisions may be made, (1) that in which the banding or gneissic structure is due to the more or less perfect segregation of the different components in bands in a fairly homogeneous rock, and (2) that which is due to the stringing out in long dike-like strips of one or more minerals foreign to the body of the rock, as that of the feldspar and pyroxene bands

*Geological Magazine, Vol. XXII, p. 441.

†*Ibid.*, Vol. XVI, p. 370.

‡Quart. Jour. of the Geol. Soc., 1878, p. 778.

in the peridotite. The two are not always distinct, but the division will aid in understanding the phenomenon. The first is conceived to be due to movement during or just preceding the crystallization in a homogeneous magma; the second, to the slight mixing during movement of a heterogeneous magma. A description of the former will be taken up first.

In some portions of the gabbro which are perfectly massive there is noticeable a slight tendency to the segregation of the different components. In this part of the rock, as well as in that which is homogeneous and massive, there could not have been much movement during solidification. Suppose, however, that in such a magma, in which there is a tendency to local segregation, a differential movement should take place, there would result a drawing out of the segregated parts of some or all of the constituents to form a gneissic structure. This is best illustrated in the case of the troctolite where the olivine is drawn out in irregular elongated patches which, when they are discontinuous, simulate very closely the structure of a gneiss, without, however, any tendency to schistosity. Wherever these shreds become continuous, the different characters may sometimes be observed in the same hand specimen, and there is presented a rude banding. From the latter to the most perfect banding there are all degrees of transition. The feldspars between the shreds or bands of olivine show no common orientation or other signs of having undergone movement during crystallization, and it must be held that the banding was assumed before the crystallization of the feldspar at least. The olivine may have crystallized before or during the movement, probably the latter, and to this fact be due its occurrence in aggregates of many small grains.

In the case of the troctolite there is no possible support for the view that the gneissic structure is due to the mixing of heterogeneous magmas. Given certain conditions of the magma favorable to the segregation of the different components, perhaps in this case of the olivine alone, and a movement of the mass on itself, and the structure described could conceivably be produced. This structure is in no way due to the linear arrangement of the individuals of either of the components, for they have a typical granular form, but rather to the lineation of aggregates. From the almost massive

troctolite in which the olivine grains are segregated in irregular patches, there can be traced a gradual transition to elongated aggregates rudely parallel, and to the appearance of more or less continuous bands of the two constituents. In the case of this rock, which is found in a number of places, the phenomenon is the simplest and most easily explainable. In the transitions to the normal olivine gabbro the same structure is to be seen in its various stages of perfection. The gneissic structure is more particularly connected with the presence of the stringy olivine aggregates. The most perfect banding occurs generally in rocks in which olivine is not an important constituent. This banding is first noticeable in the massive gabbros in the partial segregation of the feldspars and the ferro-magnesian silicates in layers, so that on a clean surface there are indistinct bandings reproduced. It is sometimes noticeable only on the weathered surfaces through the removal of the dark constituents. In portions of the gabbro where this structure is most common it is far from being uniform, and there are quite abrupt transitions from the obscurely banded or gneissic rock to one in which the banding is comparatively regular. As a general thing the bands are not continuous for any great distance, but thin out and are replaced by others. There is an exception, however, in the case of the gabbros near Point Morrito, where the bands are exceedingly regular for many feet. The variation in thickness is particularly noticeable in the case of the feldspar, while the olivine is always found in very thin bands. In some facies of the rock the banding appears only in the microscopic examination. A dark but apparently massive hypersthene troctolite showed, in thin section, the hypersthene and feldspar together in a narrow band to the total exclusion of the olivine, and another band of feldspar almost free from hypersthene. In this specimen the olivine aggregates show no noticeable lineation.

A specimen obtained at the foot of the cliffs near the Head is quite remarkable. The rock contains in order of their importance augite, brown hornblende, olivine, feldspar, hypersthene. A hand specimen three inches wide showed the following bands: First, one in which hornblende is the most important dark mineral, then a band of augite one-half inch wide, having on each side a very nar-

row band of feldspar, then hornblende with some feldspar, followed by narrow bands of feldspar not strongly marked. The augite occurs in a band free from the other constituents, having a predominating number of the crystals with their vertical axes approximately normal to the walls.

Banding is also exhibited in an interesting manner by many of the narrow basic dikes which are among the latest of the intrusions. It is due mainly to the unequal distribution of the feldspar. It is hard to understand how the banding in this case can be due to aught else than movement in an originally homogeneous magma, in conjunction with a tendency to segregation and slight differences in time of consolidation of the different components.

The dike of serpentine in the gabbro west of Point Morrito which contains the abundant inclusions of gabbro has already been mentioned. The inclusions range in size from three inches in greatest diameter down to mere specks, and are so arranged as to give the appearance of banding. It would seem that here is a clue to one of the causes of the phenomenon under consideration. The inclusions would play the part, during movement, of constituents already solidified. The body of the dike which consists wholly of diallage and decomposed olivine is distinctly banded in several places by lighter colored feldspathic layers. These are quite sharply bounded and it is quite possible that they are due to the mixing of two heterogeneous magmas.

The large body of feldspathic wherlite or picrite inclosed in the gabbro presents a linear arrangement of the feldspathic aggregates which are dotted thickly through it. These aggregates are not massive but consist of feldspar and serpentine in about equal proportions. They are frequently drawn out in lenticular patches two or three inches long. Segregation must have been contemporaneous with movement. In the peridotite at Point Morrito there are areas in which the diallage and olivine have been segregated in large bunches, but unaccompanied with movement. In other spots there are irregular patches of picrite in a matrix consisting chiefly of olivine. In both of these cases a differential movement at the time of consolidation would have produced banding.

The feldspathic streaks occurring in the dunite and other varie-

ties of the peridotite are probably due to the mixing of two partially differentiated magmas. They have not been subsequently intruded, for no sharp line of contact is visible, and the darker portions shade off into the serpentine. This is illustrated along the base of the cliffs at Point Morrito. Below the olivine-pyroxene rocks there are parallel banded layers, which, although differing from each other considerably and appearing on first examination to be dikes, yet show more or less blending across the strike.

Banding of the kind observed at Point Sal is a common characteristic of the deep-seated basic rocks in many parts of the world. Prof. A. C. Lawson* says of the anorthosites of Beaver Bay, north shore of Lake Superior: "The original allotriomorphic granular structure has not been disturbed, and it is highly improbable that the banding is in any way associated with shearing action after the final consolidation of the rock. It seems to the writer to be essentially due to some local chemical differentiation associated with movement in the thickly viscous magma prior to crystallization."

Bailey† mentions a banding in the gabbro of the Lake Superior region. He describes it as being confined to the peripheries of the great gabbro area. "The thickness of the bands ranges from 20 or more feet down to the fraction of an inch only."

Banding of the type under discussion is very prominent in many portions of the British Islands, and the English geologists have given a great deal of study to the question. Bonney and McMahon‡ describing the crystalline rocks of the Lizard District note a banding or foliation in the serpentine. They say: "In the opinion of the authors the structure can only be explained as a fluxion-structure, that is to say, as being the result of traction acting on either an imperfectly blended mixture of two magmas, differing slightly from each other in composition, specific gravity, or fluidity, as in the case of the banded felsite or rhyolite, or on a mass in which complete crystallization has been arrested by subsequent motion, at a time when only a portion of the constituent minerals had separated

*Bull. No. 8, Minn. Geol. Survey, p. 15.

†Journal of Geology, Vol. II, p. 817.

‡Quart. Jour. of the Geol. Soc., Vol. XLVII, p. 474.

themselves out from the magma." They state that no signs of crushing are apparent in the rock.

Bonney* noted a similar appearance in the lherzolite of the Lac de Lherz, which he attributed to a "fluidal structure."

McMahon† advanced the following opinion to account for the foliation of the Lizard gabbros: "That the latter was produced by 'shearing motion' on the rock after its consolidation had advanced considerably, but was still incomplete." He notes also a rapid passage in some of the dikes from a foliated to granitic structure, and attributes the latter to greater solidification.

Harker‡ describes a mottled appearance in some hornblende picrites due to the "mingling of dark and light patches or the separation of white spots on a black ground," and also a banding, as follows: "This last-mentioned appearance seems to be caused by the difference between bands alternately rich and poor in olivine, a character noted by Reusch in the saussurite gabbros of the Bergen district. There are even distinct bands less than an inch in width, which under the microscope appear as veins entirely composed of serpentinized olivine with much secondary magnetite."

Teall§ in an article on the metamorphosis of the Lizard gabbros considers the foliation the result of pressure or regional metamorphism, saying: "Is it an original or secondary structure? That it is due to a differential movement in the mass after the separation of the original constituents will I think be admitted on all sides. The only question that can arise is whether the movement was in any way connected with the intrusion of the rock."

Geikie and Teall‖ have given in detail the structure of some Tertiary gabbros in the Isle of Sky. They recognize four distinct varieties: "(1) dark, fine-grained granulitic gabbros, resembling externally basalt rocks; (2) well-banded gabbros composed of irregularly alternating bands and laminæ of the several constituent minerals; (3) coarse massive gabbros destitute of any banding; and (4)

*Geological Magazine, Vol. XVI, p. 370.
† *Ibid.*, Vol. XXIV, p. 76.
‡Quart. Jour. of the Geol. Soc., Vol. XLIV, p. 457.
§Geological Magazine, 1886, p. 489.
‖Quart. Jour. of the Geol. Soc., 1894.

pale feldspathic veins." Their description of the banded portion is as follows: "Each of these banded sheets consists of many parallel layers of lighter and darker material. The component layers vary in thickness from mere pasteboard-like laminæ to beds a yard or more in thickness. On a single exposed face of rock they may be seen to be as parallel, regular, and continuous as sedimentary deposits. An intimate union exists between the material of the successive bands. They are welded into each other by the mutual penetration of their component minerals." In the locality described the authors have not noticed any lineation of the individual crystals, although in some of the gabbros of the Inner Hebrides there is present a flow structure with drawn-out feldspars. "The more basic portions are not confined to the margin of the masses, but alternate with the more feldspathic portions to form the banded complex." They believe that the anorthosite rocks of Canada originated under much the same conditions. In conclusion the statement is made that "the banding is the result of the intrusion as sills of a heterogeneous magma, the heterogeneity produced by causes operating elsewhere and probably at lower levels in the earth's crust. Then came the intrusion of the heterogeneous magma as sills, and it was by the deformation of the molten mass during intrusion that the banded structure was produced."

It is the opinion of the author that the banding at Point Sal is in large part due to other causes than that of a differentiated magma which subsequently underwent differential movement; that this was concerned, but that it alone could not have produced the phenomena.

The most perfect banding at Point Sal resembles closely that in other regions which have been referred to, and generally considered to represent the mingling of heterogeneous magmas during movement, but the fact that here there is plainly to be discerned transitions from the regular and even banding to that of discontinuous bands, then to the gneissic structure, and finally to the massive condition, leads irresistibly to the conclusion that here at least the different portions of the rocks in which banding is pronounced solidified from what was a fairly homogeneous magma previous to movement. There was, however, a tendency to the segregation on

a small scale in certain portions of the magma as the temperature lowered prior to consolidation, and in conjunction with this a movement of the magma on itself took place in the conduit. These two things, taken together with the fact that there were slight differences in the time of crystallization of the different constituents, would tend to produce linear aggregations of more or less purity. It seems that the greater part of the segregation took place during the movement, but that this was not a segregation of partially consolidated material, except perhaps the olivine, for the crystals of the different bands present no more appearance of movement during their period of formation than do those of the massive varieties. The layers interlock as Geikie and Teall have described. It is quite probable that the olivine, which always occurs as aggregates of numerous small grains, crystallized during the movement, but in the case of the feldspars movement must have ceased when they began to form. None of the other dark silicates show such peculiar stringy masses as the olivine.

Discussion of Magmatic Variation.—It is not the plan here to enter into any detailed discussion of the question of differentiation in rock magmas. The work done in this line has been thoroughly discussed by Iddings, Brögger, Rosenbusch, and others. The sequence, however, of the intrusions at Point Sal will be discussed, as well as their relation to similar rocks in California and other parts of the world.

Iddings* states the general law of differentiation to be as follows: "The variation in the composition of igneous rocks, which constitute a series of eruptions at any volcanic center, is the result of the chemical differentiation of some intermediate magma." "The general succession is from a rock of average composition through less silicious and more silicious ones to rocks extremely low in silica and others extremely high in silica, that is, the series commences with a mean and ends with the extremes."

Geikie† has formulated the general succession of eruptive rocks in Great Britain as follows: "With the important exception of the Snowdonian region, and possibly others, we find that the earlier

* Bull. Phil. Soc. Wash., 1892., pp. 151, 145.

† Quart. Jour. of the Geol. Soc., Vol. XLVII.

eruptions of each period were generally the most basic, and that the later intrusions were the most acid."

Teall * says: "Given one reservoir and continuous cooling there would be one sequence, the basic rocks should precede the acid. This has been the case in many regions, but the rule is by no means without exceptions. The exceptions may be due to the existence of two or more reservoirs or to the accession of heat or of fresh material during the process of consolidation."

In a paper by Geikie and Teall † there are some interesting observations on the differentiation of magmas: "We often find what is a connected series of intrusions exhibiting a wide range in chemical and mineralogical composition, and certain definite though probably not very great differences in age. Such a plutonic area taken as a whole, though forming a petrological complex, is a geological unit. The complexity in such cases can not wholly be accounted for by differentiation *in situ*. The more abrupt changes require the hypothesis of successive intrusions, which probably represent differentiation elsewhere of the same general character as that which has taken place to a smaller extent *in situ*. We recognize, therefore, two kinds of petrological complexity in plutonic areas, (1) differentiation *in situ*, (2) successive intrusion."

In the study of the Yogo Peak igneous rocks, Pirsson ‡ found a progressive differentiation from one end to the other of a large intrusive mass, to which he applied the term "facies suit," after Brögger, who used it to designate the differentiation of a mass in its final resting place. Mr. Pirsson also found in the rocks of Square Butte, in Montana, a progressive increase in the ferro-magnesian silicates toward the outer border.

Brögger § reaches the conclusion that there is a fairly common sequence. "The series basic, less basic, acid appears so often among the deep-seated rocks that we must look upon this series as a normal one; the sudden return to the basic is known in many occurrences, but appears to fail often. . . . The deep-seated

* Nat. Sci., Vol. I, No. 4.

† Quart. Jour. of the Geol. Soc. 1894.

‡ Am. Jour. of Sci., Vol L, p. 467.

§ Die Eruptionsfolge der Triadischen Eruptivegesteine in Sudtyrol.

rocks of one period of eruption are the differentiation products of a common magma basin. The differentiation is brought about by a diffusion according to the order of crystallization toward the outer surface. The more remote the periods of eruption, the more differentiated should be the products erupted. . . . The series of surface rocks is not necessarily the same as that of the deep-seated rocks. These are in large part controlled by secondary differentiation, being a repetition of basic, acid, basic, etc." He says that most authors have not made this distinction. In conclusion he adds: "In general, the farther the magma basin is removed from the magma trunk, the greater the amount of differentiation which has taken place, so much less regularity will there appear in the series of eruptions. Any irregularity or departure from the rule in the deep-seated rocks must be all the more pronounced in the surface rocks." Brögger also emphasizes the point that his sequence is that for regions removed from mountain-making influences.

In many respects the views of the investigators quoted do not differ greatly. It would seem, however, that in the majority of instances there are complicating causes at work which so affect the series of eruptions that no statement can be formulated which will hold true in all. Iddings' view of continually greater extremes in the character of eruptions of any one period from a common reservoir is only one aspect of the truth, of which that of Teall and Brögger, of a continually increasing acidity, is another. In mountain regions, where disturbances are taking place, the sequence must of necessity be different in many cases from that which would occur theoretically in a magma and its apophyses when not so affected.

At Point Sal there can be observed both kinds of petrological complexity described by Geikie and Teall, differentiation *in situ* and successive intrusion. The gabbro and peridotite were each fully differentiated in some deeper-seated region, while in each secondary differentiation took place during the movement upward or after attaining its present position. Judging from the surface exposures the gabbro can not form more than one-fourth of the total mass, and it may be less, so that the common magma must still have been very rich in magnesia. Owing to the fact that not all the different

kinds of dikes appear in any one spot, their succession can not always be determined. The main body of the gabbro, and perhaps some of the diabase along the northern side of the complex, are undoubtedly the oldest of the intrusions. The peridotite at Point Morrito has been intruded through the gabbro and is apparently continuous with the large body of altered dunite toward the east. At Point Morrito there are dikes of greatly varied character later than both the gabbro and peridotite. As a general thing these dikes are poorer in feldspar than the normal gabbro. They are very fine grained, but granular in structure. The dikes of diabasic character occur in many parts of the complex, in both the gabbro and peridotite.

The succession, as far as determined, is as follows: gabbro and some diabase, peridotite, dikes of granular structure and intermediate composition, diabase and ophitic quartz-diorite, and feldspathic veins. A partial analysis was made of the feldspar in the banded troctolite, with the following result: SiO_2 42.6, Al_2O_3 38.3, CaO 18.65. An estimation of the silica in the partially altered dunite resulted in 41.3 per cent. This would give an extreme range in silica between the peridotite and the ophitic quartz-diorite of 24.7 per cent. If the pegmatitic quartz-feldspar veins were taken into account, the range would be still greater, for in them the silica reaches 73 per cent. The succession in general is basic, more basic, and acid. The occurrences of the acid rocks are, however, comparatively insignificant in volume. The larger number of the various eruptive bodies do not differ much as far as the silica content is concerned. It is, however, when we look away from the silica ratio to that of the alumina, magnesium, and calcium, that the extreme differences in mineralogical composition are understood.

In addition to the very common association of diabase and peridotite in many parts of the state, there are localities where gabbro is also found with peridotite. Whether this gabbro is of later origin, or fragments of an earlier consolidation, or secretions from the magma, observation as yet seems not to have definitely settled. It is a well-established fact of common occurrence to find inclusions of foreign bodies in the peridotite. This is particularly prominent at Knoxville, Lake County, and on Angel Island. Although Point Sal is

the only spot yet known where the feldspathic separation preceded the peridotitic, yet it is certain that the latter is almost invariably followed by dikes of diabasic character.

The magma basin, from which these numerous bodies of peridotite were derived, could have been no local one. They occur through nearly the whole length of California west of the Sierra Nevada, and extend for an unknown distance northward. As far as the author's observations have been carried, there appears to have been only one period of intrusion in the Coast Ranges. The eruptions cut strata of Knoxville age and are overlain by the Chico. The diabase sometimes occurs on one side of the peridotite and sometimes within it, but at Point Sal, if there can be any distinction made, it is that the magnesian rocks are confined more to the center of the mass, and the feldspathic to the borders. The various masses reached their present position already fully differentiated. Secondary differentiation took place in both the feldspathic and magnesian facies, but whether the distinct bodies of gabbro, diabase, and peridotite are segregations in the common magma basin of the "petrographic province" or in the conduit through which the local protrusion took place, is difficult to say, although it would seem that the probabilities are in favor of the latter view.

If the view that the crust of the globe becomes progressively more dense and basic with increased depth is a correct one, then the peridotites when they are not merely facies of more acid rocks must be conceived as originating at great depths. This basic material forced up through fissures over a wide area on the Pacific Coast, occurring everywhere as independent masses, and not mere basic secretions from an acid magma, indicates that it originated in a deeper basic portion of the crust. Under the conditions of great pressure and high temperature existing at great depths, diffusion would be impossible and the composition would remain homogeneous. The absence of any large bodies of acid rock which appear genetically related to the peridotites strongly supports the view of the existence of a widely distributed basic magma of nearly homogeneous composition. The differentiation which has taken place in this basic magma in the chimneys has been a very complete one as a general rule. The gabbro is fully as feldspathic near the perido-

tite as at any other point, while the feldspar in the latter is apparently due more to resorption than to a lack of differentiation. The extreme variations in the gabbro are due to secondary differentiation, while the dikes of intermediate character in the peridotite represent either a differentiation of the latter or a partial resorption of the feldspathic facies at a greater depth. Where differentiation has taken place on a small scale, as at Point Morrito, resulting in stringy masses and nodules of the different constituents only a few feet in diameter, it would seem that the phenomenon could not be due to differences of temperature and pressure, but, under favorable circumstances of great liquidity and slow cooling, to a tendency to segregation of similar molecules through chemical affinity.

The theory which Rosenbusch* has advanced to account for the differentiation of homogeneous magmas seems to be applicable more than any other to the phenomena observed here. He conceives that the original magma within the earth was homogeneous, and that it separated into partial magmas of different composition according to the laws of chemical affinity. The two extremes of this process he terms the *foyaite* $(NaK)AlSi_2$, and the *peridotite* (MgFe)Si magmas, with an intermediate one ($CaAl_2Si_4$). As the last increases in amount, the "metal kern," representing the *peridotite* magma, becomes more easily soluble in that of the *foyaite* magma.

There is certainly shown here a tendency to the separation of certain molecules independent of differences in temperature. One of these is rich in magnesia and iron, the other in calcium and alumina.

Geological Laboratory,
University of California, May 1, 1896.

*Min. u. petr. Mitth., Vol. XI, pp. 144-178.

EXPLANATION OF PLATE 20.

The letters in the illustration refer to the following minerals: F, feldspar; P, pyroxene; A, analcite and its alteration products; M, magnetite; G, glass.

FIGURE 1.—Volcanic ash in the lower Miocene, showing the pumiceous glass occasionally inclosing feldspars. × 20.

FIGURE 2.—Augite-teschenite in which the feldspars are partially replaced by a pegmatitic intergrowth with secondary feldspar. × 20.

FIGURE 3.—Panidiomorphic facies of the augite-teschenite. The analcite occurs in large areas bounded by the idiomorphic faces of the other components. The magnetite is later than both augite and feldspar. × 20.

FIGURE 4.—Large augite plate with poikilitic structure. There are shown seven small polyhedral areas of altered analcite, partly in contact with the augite and partly inclosed in the feldspars. × 21.

FIGURE 5.—A large plate of augite containing feldspar crystals of various sizes and often showing jagged terminations. Disconnected areas of altered analcite appear in the center of the augite crystal and are bounded in part by crystallographic planes of the latter. × 20.

FIGURE 6.—Another of the poikilitic augite crystals from the teschenite. Is contains small lath-shaped feldspars, while on one edge there is a large area of analcite which penetrates the augite and it bounded by crystal planes of the latter. × 20.

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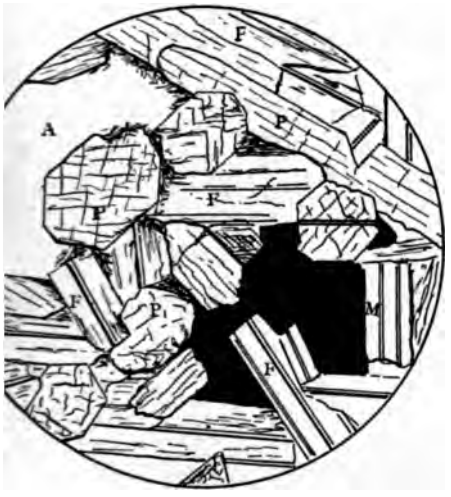

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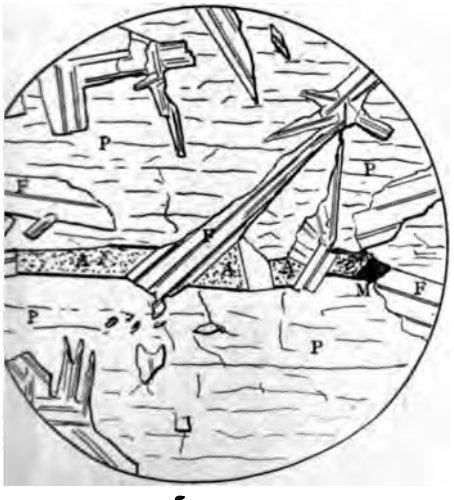

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UNIVERSITY OF CALIFORNIA
Bulletin of the Department of Geology
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ON

SOME PLIOCENE OSTRACODA

FROM

NEAR BERKELEY, CALIFORNIA,

BY

FREDERICK CHAPMAN.

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GEOLOGICAL RELATIONS.

IN the latter part of last year Prof. T. Rupert Jones kindly handed to me for description several specimens of rocks of Pliocene age containing numerous Ostracoda. These rock specimens had been sent to Prof. Rupert Jones by Dr. J. C. Merriam, of the University of California, who wished a detailed examination of them to be made, since the Ostracoda appeared to be of exceptional interest. In one of the letters accompanying the specimens Dr. Merriam says: "The Ostracoda occur at several horizons in the Pliocene near Berkeley, California. Some of the fossiliferous beds are important geological features of the country, and extend for several miles through a region in which few other invertebrate fossils are known."

For this reason Dr. Merriam thinks the Ostracoda may be of considerable use in determining horizons.

The following note on the Ostracod-bearing rocks has since been kindly furnished by Dr. Merriam. I quote it here in full:—

"The Ostracods occur in a very thick series of conglomerates,

clays, limestones, and eruptives, which is well developed in the hills east of Berkeley, California, and belongs, according to Prof. A. C. Lawson, to the lower division of the Pliocene.* They are found at various horizons in clays and limestones, from the lower to near the upper portion of the series.

"Most of the localities at which the Ostracoda were abundant (Nos. 585, 589, 26, 297), seem to be near the middle portion of the series. Here they are enormously abundant, often forming layers of impure limestone a foot or more in thickness. The limestone strata, of which there are usually several, alternate with beds of either clayey or tufaceous material ten or more feet thick. The conditions favoring growth and multiplication of the Ostracoda seem to have been particularly favorable in this region during the period in which these limestone beds were laid down. Lower down in the series, at locality No. 587, Ostracoda are quite abundant in a soft blue shale. Near the top of the section they are frequently present, but not in such numbers as to form a marked feature of the rocks."

LOCALITIES.

The five rock samples received are localized as follows: "No. 585.† Wild Cat Cañon, opposite the Caves." From this locality two specimens were received. One is an extremely hard and compact limestone, of a pale brown color, and crowded with the carapaces of Ostracoda. This rock appears to have undergone a certain amount of compression, for the surfaces of the Ostracod-valves are impressed and indented by one another; and it is due to this fact that not very many valves were obtained from this specimen, which could be definitely described. The other specimen is from a friable calcareous rock of an ocherous brown color. This rock is almost entirely made up of the valves of Ostracoda.

"No. 587. Railroad cut, one-eighth of a mile north of Bryant station, C. & N. R. R., San Pablo Valley." This somewhat shaley

*"The geology of the region in which this series occurs has been subjected to detailed study by Professor Lawson, who is preparing a monograph on the subject."—J. C. M.

†The numbers here used refer to numbered fossil localities, a record of which is kept at the State University.

argillaceous sandstone, of a bluish-grey color, yielded only a few separate valves of Ostracoda.

"No. 589. Wild Cat Cañon, one-fourth of a mile south of the Caves." This is a greenish-grey marl in which occur bands of Ostracod valves thickly massed together.

"No. 26. East side of San Pablo Ridge, one and three-fourths miles northwest of Orinda Park." A dark, impure-looking limestone crowded with Ostracoda very perfectly preserved and stained nearly black.

"No. 297. Bollinger Cañon, twelve miles southeast of Berkeley." A pale ocherous limestone, somewhat friable, and largely composed of the valves of Ostracoda.

All of the Ostracoda here described are such as inhabit fresh water at the present day, with the exception of *Cypridopsis*, which is as often found in brackish water. They are comprised in the family of the CYPRIDÆ.

It should, however, be borne in mind that in describing Ostracoda from the carapaces alone, and without any of the soft parts, the determination of species and even genera is more or less provisional.

I will here express my indebtedness to Prof. T. Rupert Jones, who has aided me greatly in regard to points of affinity respecting these specimens, as well as by his generous and invaluable advice throughout the writing of this paper.

DESCRIPTIONS.

Cypria, Zenker, 1854.

Cypria subangulata, sp. nov., plate 3, figs. 1–3.

Valves subreniform; greatest height slightly more than half the length. Anterior end broader than the posterior; both rounded, excepting at the antero-ventral region, where the outline forms a blunt angle. The dorsal edge is subangulate a little in front of the middle; the ventral edge slightly sinuous behind the middle. The valves are steeper towards the ventral margin. Length, one-fortieth of an inch; height, one-seventy-second of an inch.

This species resembles *Cypria lævis* (O. F. Muller)* in the subangulate character of the dorsal margin. It differs markedly from that form, however, in the great compression of the valves as seen edgewise, the anterior end being quite sharp. In this latter characteristic the form reminds one of *Cypria Ophthalmica* (Jurine);† but distinctly differs from it in the general outline of the valves.

Cypris subangulata occurs at locality No. 589, Wild Cat Cañon, where it is rare; and at locality No. 26, San Pablo Ridge, fairly common.

Cyclocypris, Brady and Norman, 1889.

* *Cyclocypris Californica*, sp. nov., plate 3, figs. 4–6.

Valves sub-ovate tumid. The posterior end broad and well-rounded. The anterior edge meets the ventral margin somewhat sharply, forming a decided angle. The dorsal margin strongly curved, the ventral hollow towards the middle. In edge view the carapace is rounded posteriorly and the anterior end is obtuse. Length, one-twenty-fifth of an inch; height, one-fortieth of an inch.

Cyclocypris globosa (G. O. Sars)‡ differs from the above species in having both the anterior and the posterior ends of the valves narrower, and the dorsal margin more strongly arched; the thickness of the carapace is uniformly greater than in *C. Californica*.

This species, of which only one specimen was found, occurred at locality No. 589, Wild Cat Cañon.

Cypris, Müller, 1785.

Cypris procera, sp. nov., plate 3, figs. 7–9.

Valves elongate reniform. Length, nearly twice as great as the height. Greatest height slightly in front of the middle. The

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* *Cypris lævis*, Müller, 1785, Entom., p. 52, pl. III, figs. 7–9. *C. ovum*, Brady, 1868, Mon. Rec. Brit. Ostrac., p. 373, pl. XXIV, figs. 31–34, 43–45, and pl. XXXVI, fig. ♀

† *Monoculus ophthalmicus*, Jurine, 1820, Hist. des Monocles, p. 178, pl. XIX., figs. 16, 17. *Cypris compressa*, Brady, Crosskey and Robertson, 1874, Monog. Postert. Entom., p. 123, pl. I, figs. 5, 6.

‡ *Cypris globosa*, G. O. Sars, 1863, Om en i Sommeren, 1862, foretagen Zoologisk Reise i Christianias og Trondhjems Stifter, p. 127. *Cyclocypris globosa*, Brady and Norman, 1889, Trans. R. Dublin Soc., ser. II, vol. IV, p. 71, pl. XIV, figs. 1, 2.

anterior and posterior extremities compressed and sharp. Dorsal margin well arched; ventral margin slightly hollow; ventral edges of valves sinuous and mutually overlapping. End view of carapace, ovoid, but pointed. Length, one-twentieth of an inch; height, one-thirty-sixth of an inch. In general outline this Ostracod shows some resemblance both to *Cypris virens* (Jurine),* and to *Cypridopsis* (?) *Newtoni*, Brady and Robertson.† As regards the first-named, however, our specimens are too low, the dorsal margin is not so strongly curved, and the posterior margin is less rounded and narrower. Whilst as distinguished from the latter form, the Californian specimens have more evenly pointed ends, with the posterior region scarcely thicker than the anterior; and, moreover, the anterior border of the valve is more evenly rounded. It is difficult to determine without doubt the generic affinities of these specimens, but they probably present most points of resemblance to the genus *Cypris*, and, moreover, show the feeble overlapping of the edges o the valves, which is somewhat characteristic of the genus.

Cypris procera was found at locality No. 589, Wild Cat Cañon, one specimen; and at locality No. 297, Bollinger Cañon, one specimen.

Erpetocypris, Brady and Norman, 1889.

Erpetocypris Merriamiana, sp. nov., plate 3, figs. 10–12.

Shell laterally sub-reniform, highest at the middle. Anterior and posterior extremities obliquely rounded. Dorsal margin strongly arched; ventral border sinuous, hollowed near the middle. The antero-dorsal region depressed and hollowed. Ventral edge view sub-pyriform; well rounded and swollen at the posterior end, and tapering to a sharp edge anteriorly. Length, one-seventeenth of an inch; height, one-thirtieth of an inch.

This striking species does not exactly correspond with any of our recent types, but seems to be not far removed from *Erpetocypris tumefacta* (Brady and Robertson).‡

*See Brady, Crosskey, and Robertson, 1874, Mon. Post-tert. Ertom., pl. II, figs. 27, 28.

†*Idem*, *ibid.*, pl. II, figs. 20, 21.

‡See Brady and Norman, 1889, Trans. R. Dublin Soc., ser. II, vol. IV, p. 87, pl. VIII, figs. 5–7.

The hard limestone from locality No. 585, Wild Cat Cañon, is for the greater part composed of the carapaces of this species. It is also found in the friable specimens from the same locality, where it is common; and at locality No. 297, Bollinger Cañon, where it again forms the greater part of the rock.

Erpetocypris lata, sp. nov., plate 3, figs. 13–15.

Valves bean-shaped laterally. Dorsal edge strongly arched and rounded off towards the ventral side, which is nearly straight. In edge view this form somewhat resembles the previous one, but the carapace is not so full in *E. lata*, and the posterior extremity not so well rounded in the aspect mentioned. Length, one-twelfth of an inch; height, one-twenty-fifth of an inch.

At locality No. 585 this species is frequent; and at locality No. 297, Bollinger Cañon, two specimens.

Cypridopsis, Brady, 1868.

Cypridopsis pliocænica, sp. nov., plate 3, figs. 16–18.

Valves sub-ovate, ends evenly rounded; highest, near the anterior end of the valve. Dorsal edge strongly curved; ventral margin straight. Carapace somewhat compressed, but with the ventral border fairly steep, or blunt in edge view. Length, one-twenty-sixth of an inch; height, one-forty-fourth of an inch.

The above form appears to be closely allied to *Cypridopsis vidua* (Müller)* in their general outline; but the two forms have many points of difference. The carapace of *C. pliocænica* is compressed as compared with *C. vidua*. In the latter species also the ventral margin is incurved, whilst that of *C. pliocænica* is nearly straight.

It is interesting to note here that the genus *Cypridopsis* contains species which are found in brackish as well as fresh water.

C. pliocænica was found at locality No. 587, San Pablo Valley, two specimens.

Candona, Baird, 1850.

Candona candida (Müller), var. *depressa*, nov., plate 3, fig. 19.

This is a variety not altogether unlike *C. candida* var. *tumida*,

**Cypridopsis vidua*, Brady, 1868, Mon. Rec. Brit. Ostrac., p. 375, pl. XXIV, figs. 27–36, 46.

Brady and Robertson,* in general outline, although our specimen is less regular in shape, having a sinuosity on the dorsal edge a little in front of the middle, whilst the ventral edge is more or less flexed along its length. The carapace also is greatly compressed as compared with the above-mentioned variety. The carapace is highest just behind the middle. Length, one-fifteenth of an inch; height, one-twenty-seventh of an inch.

One specimen was found at locality No. 589, Wildcat Cañon.

Candona lactea, Baird, var. *acuminata*, nov., plate 3, figs. 20–22.

This variety differs from recent specimens of the type form in having a distinctly acuminate front to the carapace. Otherwise it appears in its lateral aspect to agree with the figures given under the name of *C. detecta*,† but latterly referred to the species *C. lactea*.‡ Length, one-twenty-fifth inch; height, one-forty-second inch.

† *C. lactea*, var. *acuminata*, is very rare at locality No. 585, Wildcat Cañon, opposite the Caves; at locality No. 26, San Pablo Ridge, it is frequent; and at No. 297, Bollinger Cañon, it is rare.

† *Candona gracilis*, sp. nov., plate 3, figs. 23–25.

Shell in lateral aspect long elliptical, rounded at both ends. Dorsal border well arched, ventral border slightly incurved. The edge view shows that the carapace is fullest in front of the posterior third, and that both ends are acuminate. Length, one-thirty-eighth of an inch; height, one one hundred and fifteenth of an inch.

Among the elongate forms of *Candona* there are none so regularly elongate as the above, but of the attenuate and fabiform examples, *C. acuminata* (Fischer)§ may be especially mentioned.

The above species was found at locality No. 589, Wildcat Cañon.

London, England, May, 1896.

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*Ann. Mag. Nat. Hist., ser. IV, vol. VI, 1870, p. 16, pl. IX, figs. 13–15. See also Brady and Norman, Trans. R. Dublin Soc., ser. II, vol. IV, 1889, p. 98, pl. X, figs 14–17.

†See Brady, Crosskey, and Robertson, 1874, p. 134, pl. I, figs. 7–9.

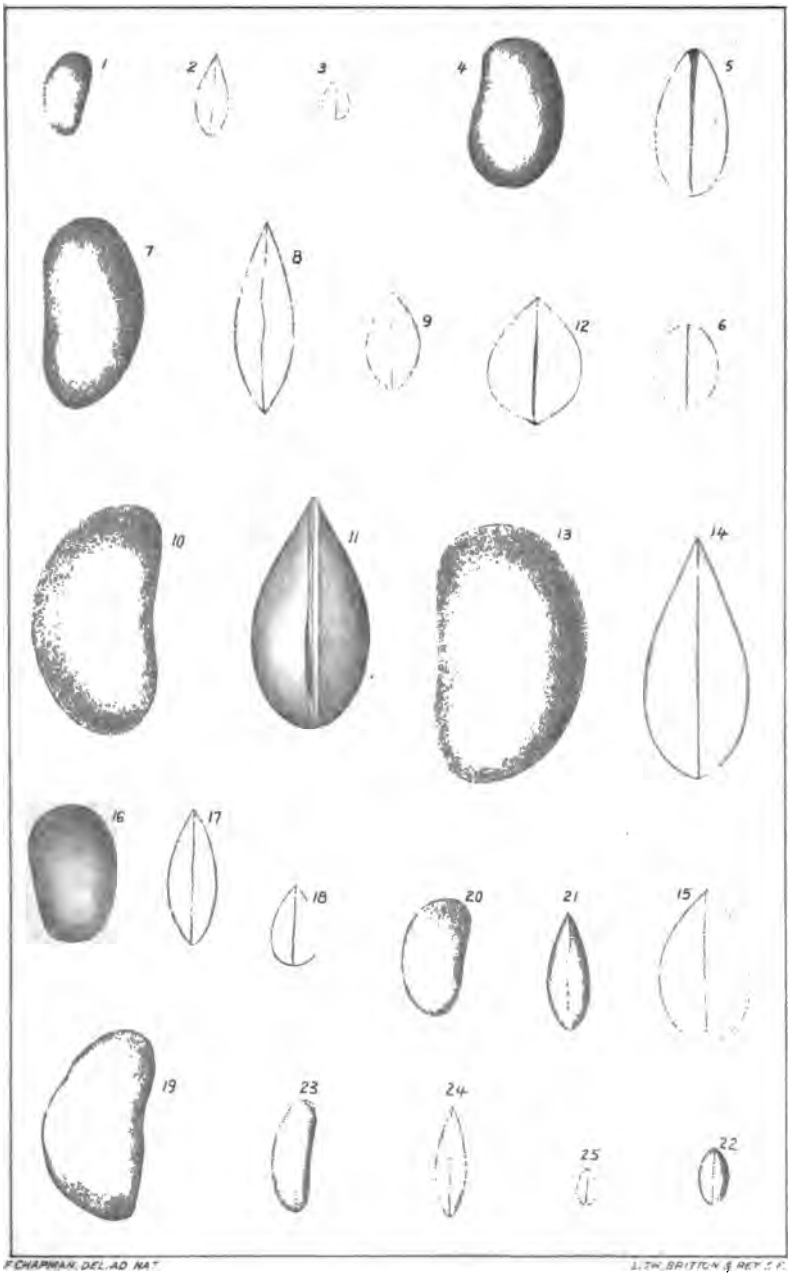
‡Brady and Norman, 1889, Trans. R. Dublin Soc., ser. II, vol. IV, p. 100.

§See Brady and Norman, Trans. R. Dubl. Soc., ser. II, vol. IV, 1889, pp. 104, 105, pl. IX, figs. 9, 10; pl. X, figs. 5, 6.

EXPLANATION OF PLATE 3.

The figures in this plate represent the valves and carapaces with the anterior end upwards. The height of the valves is therefore shown by the transverse width in the figures. In the edge views the tranvserse width is the thickness.

FIGURE 1.—*Cypris subangulata*, sp. nov. Lateral view, right valve. × 18.
FIGURE 2.—*Cypris subangulata*, sp. nov. Edge view. × 18.
FIGURE 3.—*Cypris subangulata*, sp. nov. End view. × 18.
FIGURE 4.—*Cyclocypris Californica*, sp. nov. Lateral view, left valve. × 20.
FIGURE 5.—*Cyclocypris Californica*, sp. nov. Edge view. × 20.
FIGURE 6.—*Cyclocypris Californica*, sp. nov. End view. × 20.
FIGURE 7.—*Cypris procera*, sp. nov. Lateral view, left valve. × 20.
FIGURE 8.—*Cypris procera*, sp. nov. Edge view. × 20.
FIGURE 9.—*Cypris procera*, sp. nov. End view. × 20.
FIGURE 10.—*Erpetocypris Merriamiana*, sp. nov. Lateral view, right valve. × 20.
FIGURE 11.—*Erpetocypris Merriamiana*, sp. nov. Edge view. × 20.
FIGURE 12.—*Erpetocypris Merriamiana*, sp. nov. End view. × 20.
FIGURE 13.—*Erpetocypris lata*, sp. nov. Lateral view, left valve. × 20.
FIGURE 14.—*Erpetocypris lata*, sp. nov. Edge view. × 20.
FIGURE 15.—*Erpetocypris lata*, sp. nov. End view. × 20.
FIGURE 16.—*Cypridopsis pliocænica*, sp. nov. Lateral view, left valve. × 20.
FIGURE 17.—*Cypridopsis pliocænica*, sp. nov. Edge view. × 20.
FIGURE 18.—*Cypridopsis pliocænica*, sp. nov. End view. × 20.
FIGURE 19.—*Candona candida* (Müller), var. *depressa*, nov. Lateral view, right valve. × 15.
FIGURE 20.—*Candona lactea* (Baird), var. *acuminata*, nov. Lateral view, right valve. × 15.
FIGURE 21.—*Candona lactea* (Baird), var. *acuminata*, nov. Edge view. × 15.
FIGURE 22.—*Candona lactea* (Baird), var. *acuminata*, nov. End view. × 15.
FIGURE 23.—*Candona gracilis*, sp. nov. Lateral view, right valve. × 23.
FIGURE 24.—*Candona gracilis*, sp. nov. Edge view. × 23.
FIGURE 25.—*Candona gracilis*, sp. nov. End view. × 23.



PLIOCENE OSTRACODA from near BERKELEY.

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NOTE

ON TWO TERTIARY FAUNAS

FROM THE

ROCKS OF THE SOUTHERN COAST OF VANCOUVER ISLAND

BY

J. C. MERRIAM.

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Occurrence of Fossils..... 102
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INTRODUCTORY REMARKS.

THE occurrence of fossiliferous horizons of marine Tertiary on the coast of Vancouver Island having received only the briefest mention in geological literature, the following description of some interesting collections recently made on the southern coast of the island by Dr. C. F. Newcombe, of Victoria, is offered as a contribution to our knowledge of the geology and palæontology of this region.

During the years 1894 and '95 several collections of marine Tertiary shells from Vancouver Island were forwarded to the writer

by Dr. Newcombe for identification and for determination, if possible, of the age of the rocks in which they occur. The collections were all from two localities, representing different horizons of the Tertiary. The first of these is on Carmanah Point at the entrance to the Strait of Fuca, and the second near Muir and Coal Creeks, in the Sooke District. All the material was collected by Dr. Newcombe, who visited the localities, collecting fossils and studying, where possible, the stratigraphic relations of the fossiliferous beds. Up to the time of Dr. Newcombe's explorations the Tertiary fossils of Vancouver Island seem never to have been systematically collected.

CARMANAH POINT.

The collection from Carmanah Point represents the older of the two horizons, and is interesting on account of the resemblance it bears to the fauna of Conrad's Astoria Miocene,* to the greater, Miocene portion of which Dr. W. H. Dall† has given the name Astoria Group.

Occurrence of Fossils.—A section of the rocks near Carmanah Point lighthouse, forwarded to the writer by Dr. Newcombe, shows altogether about 150 feet of sandstone, shale, conglomerate and drift mantle. The occurrence of the fossils is described by Dr. Newcombe in the following note:—

"The fossils are found chiefly in the conglomerate layers, mostly in the contained boulders, which vary in size from small pebbles to four or five feet in diameter. The boulders, when fossiliferous, are of a bluish grey, fine, and very hard sandstone. The matrix of the conglomerate contains in places large quantities of broken fragments of shells, many resembling species in the boulders, but mostly too much broken up to permit identification. Several large pieces of bored fossil wood project in various parts of the section. Similar rocks extend east and west for some miles, but are very difficult of access except in very calm weather."

Dr. Newcombe's statement that the matrix between the fossiliferous boulders contains "broken fragments of shells, . . . resembling species in the boulders," suggests the idea that the boulders are of concretionary origin. This seems all the more probable as

* Geology of Wilke's Exploring Expedition, 1838–42.

† Correlation Papers, Neocene. Bull. 84. U. S. Geol. Surv., p. 225

the occurrence of fossils in concretionary boulders is not uncommon at Astoria and at various other points on the west coast, where the later Tertiary rocks are exposed. In answer to a question as to the character of the fossiliferous boulders, Dr. Newcombe stated recently that it is possible that they are concretionary, but he remembers having seen along with them, in the fossiliferous beds, large quartz and diorite pebbles and water-worn boulders. Whether water-worn or concretionary, it is pretty certain that the fossiliferous boulders are all of the same origin, since the matrix in which the fossils are imbedded seems to be the same in all cases. We may safely assume that the species cited here as occurring in the Carmanah Point beds all belong to the same fauna, which may have flourished *in situ* at the time the Carmanah Point sediments were being deposited, or may have lived in an earlier period, at a locality not far distant, from which the fossiliferous boulders were derived for the formation of the Carmanah Point conglomerate.

List of Species.—The following species* from Carmanah Point were identified in Dr. Newcombe's collection.

1. *Nucula divaricata*, Con.
2. *Doliopsis* sp.
3. *Lucina acutilineata*, Con.
4. *Mya abrupta*, Con.
5. *Tellina oregonensis*, Con.
6. *Crepidula rostralis*, Con.
7. *Dentalium substriatum*, Con.
8. *Cerithiopsis oregonensis*, Con.
9. *Priscofusus oregonensis*, Con.
10. *Cardita ventricosa*, Gld.
11. *Tellina albaria*, Con.
12. *Lunatia oregonensis*, Con.
13. *Sinum scopulosum*, Con. (*conf.*).
14. *Cylichna oregona*, Con.
15. *Pectunculus patulus*, Con.
16. *Loripes parilis*, Con.

* The synonym of the species listed, together with descriptions and figures of the new species, will form the subject of a future paper.

17. *Cytherea vespertina*, Con. (*aff.*).
18. *Trochita inornata*, Gabb. (*aff.*).
19. *Mytilus edulis*, Linn. (*aff.*).
20. *Turritella* nov. sp.
21. *Cardium* nov. sp.
22. *Cytherea* sp.
23. *Solen* sp.
24. Bored wood, *Teredo* (?) sp.

In addition to this list Dr. Newcombe has sent the following list of species, determined by Dr. W. H. Dall, in a collection made near Carmanah Point in 1890.

1. *Axinus bisectus*, Con.
2. *Chrysodomus* sp. (found in Oregon Miocene).
3. Veneroid (possibly *Clementia*).
4. *Macoma nasuta*, Con.
5. *Venus pertenuis*, Gabb.
6. *Pachypoma biangulata*, Gabb. (*conf.*).
7. *Mytilus edulis*, Linn. (*aff.*).
8. *Pleurotoma* indet.
9. *Teredo* sp.

Correlation.—Of these species numbers 1–17 of the writer's list occur in Conrad's Astoria Miocene, *Trochita inornata* (No. 18) and forms like *Mytilus edulis* (No. 19) occur in the Miocene of California, Nos. 20 and 21 are new, and the other three forms are doubtful.

Of Dr. Dall's list the *Axinus bisectus* and *Chrysodomus* occur at Astoria. A Clementia-like shell, which was seen in Dr. Newcombe's collection, looked very much like *Cytherea oregonensis*, Con., found originally near Astoria. *Macoma nasuta*, *Venus pertenuis* and forms like *Mytilus edulis*, are found in the Miocene of California. *Pachypoma biangulata* occurs in rocks of doubtful age (Neocene) in California. The species of *Teredo* and *Pleurotoma* not being identified, need not be considered farther.

The fauna of the Carmanah Point beds seems, on the whole, to be the same as that of Conrad's Astoria Miocene, excluding, however, the lower portion of the latter series, which has been supposed to be of Eocene age.

SOOKE DISTRICT.

In 1876 Mr. James Richardson noticed the occurrence of fossiliferous rocks in the Sooke District, and published the following statement regarding them.*

"At the mouth of John's River the lowest beds are grey sandstone, in some places crowded with fossils belonging apparently to three or four species. These are referable to the genera *Ostrea*, *Pecten*, and *Saxidomus* and are either of Tertiary or post-Tertiary age."

In 1892 Dr. W. H. Dall mentioned† the occurrence of marine beds of Miocene age near Sooke.

Dr. Newcombe visited the Sooke District in 1893, '94, and '95, collecting in all between twenty-five and thirty molluscan species.

The cliffs, in which the fossils occur, are stated by Mr. Richardson and Dr. Newcombe to show a considerable thickness of soft sandstone, with some conglomerate. The strata do not appear to be greatly disturbed. In places the sandstone is full of fossils, which are often well preserved.

Table of Sooke Fauna.—The following table of species gives, as nearly as can at present be determined, the composition of the fauna of the Sooke beds:—

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*Geol. Surv. of Canada Rept. Prog. 1876–77.

†Bull. U. S. Geol. Surv., No. 84, p. 230.

	Recent	Pliocene, Cal.	Miocene, Calif.	Miocene, Astoria or Carmanah Pt.	Extinct.
1. *Placunanomia macroschisma*, Desh.	*	*			
2. *Mytilus edulis*, Linn.		*	*	*	
3. *Cerithidea californica*, Hald.	*	*	*		
4. *Acmæa mitra*, Esch.	*				
5. *Crepidula rugosa*, Nutt. (*aff.*)	*				
6. *Pecten æquisulcatus*, Carp. (*conf.*)	*				
7. *Pecten hastatus*, Sowb. (*conf.*)	*	*	*		
8 *Chrysodomus dirus*, Reeve.	*				
9 *Yoldia impressa*, Con.	*	*	*	*	
10. *Pectunculus patulus*, Con.		*	*	*	*
11. *Trochita inornata*, Gabb.			*	*	*
12. *Sinum scopulosum*, Con. (*conf.*)				*	*
13. *Fusus* nov. sp. (a)					*
14. *Fusus* nov. sp. (b)					*
15. Patelloid nov.					*
16. *Nassa* (?) nov. sp.					*
17. *Ancillaria* nov. sp.					*
18. *Cytherea* nov. sp. (*a*)					*
19. *Cytherea* nov. sp. (*b*)					*
20. *Biltium* nov. sp, (?)					*
21. *Crepidula* sp.					
22. *Ostrea* sp.					
23. *Cardium* sp.					
24. *Cerithidea* sp.					
25. *Tapes* (?) sp.					

Age and Relationship of Fauna —In attempting to determine the age of the Sooke beds, a comparison of their fauna with that now existing on the Pacific Coast shows that of the twenty molluscan species determined, eleven, or about fifty-five per cent, are probably extinct, and eight or nine are pretty certainly living. Five species could not be certainly determined and should not be considered. According to the law of percentages as generally used in determining the age of Tertiary faunas, the nearly equal number of living and extinct species makes it impossible to place the beds in either the Eocene or Quaternary. The number of species listed being small, we can not place much dependence in the percentage of living species for accurate determination of the age; it is hardly probable, however, that the Miocene would contain forty-five per cent. of living species, that number indicating a period nearer the present time.

Regarding the trustworthiness of the percentage method as

applied to west coast geology, even when the number of species at hand is large, it may be stated that, while it is certainly of great value where once standardized, it is doubtful whether the percentages of Recent molluscan species found in the faunas of the different Tertiary periods in other parts of the world would correspond at all to the percentages of modern forms, which existed on the west coast during the same periods. Corresponding to variations, or lack of variation, in topography and climatic conditions, the average percentage of Recent species on the west coast in any given period may have been much larger or much smaller than elsewhere.

Comparing the Sooke fauna with that of well-known Tertiary and post-Tertiary horizons of the Pacific Coast, we find that six or seven of the species are known from the Miocene and about an equal number from the Pliocene, nine species are found in the Quaternary and Recent, and seven or eight are not known to occur elsewhere, either recent or fossil.

The fauna of the Sooke beds, as represented in Dr. Newcombe's collection, is quite different from any of the Oregon or California Miocene or Pliocene faunas known to the writer. The presence of such a large percentage of new forms, and the decided difference of the whole fauna from that of Carmanah Point, of Astoria and of the lower Pliocene of Northern California, are rather surprising when we take into consideration the relation of these faunas to each other. There are common to the Carmanah Point and Sooke beds about five species; two good and three doubtful. This is a much smaller number than we should expect to find if both horizons belong to the Miocene or even if one were lower Miocene and the other lower Pliocene. This may be explained either by supposing the interval between the deposition of the original sediments containing the Carmanah Point fauna and the deposition of the Sooke beds to have been a very long one, allowing time for radical faunal changes, or by supposing considerable topographic and climatic changes to have taken place in a shorter interval, accompanied by immigration of new forms.

Supposing the Carmanah Point and Sooke faunas to have lived at different periods along the shore of the same ocean, we can hardly suppose the latter derived from the Carmanah Point fauna by

gradual process of evolution within the limits of the middle Tertiary. Immigration and emigration must have been important factors in the change. Granting even that the greater part of the change was due to migration rather than evolution, the faunal changes, together with the climatic or topographic changes which they must necessarily have accompanied, are such as usually mark the boundaries between geological periods.

The evidence at our command indicates that the Sooke beds are of middle Neocene age, and that the time of their deposition was considerably later than that of the Carmanah Point beds.

University of California, Dec. 1, 1896.

UNIVERSITY OF CALIFORNIA
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THE DISTRIBUTION OF THE NEOCENE SEA-URCHINS OF MIDDLE CALIFORNIA AND ITS BEARING ON THE CLASSIFICATION OF THE NEOCENE FORMATIONS

BY

JOHN C. MERRIAM

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INTRODUCTION.

OF the numerous invertebrate forms known from the marine Neocene of California there are none which better aid the geologist in the determination of horizons than the echinoids. Though Neocene molluscan remains are plentiful, they are not always characteristic nor are they usually in a good state of preservation. The sea-urchins, when present at all, are usually abundant and well preserved and, having in most cases a short geological range, are of more than ordinary value in geological work.

At the present time there are eight species of sea-urchins know from the Neocene formations of California, all of which, on account of their abundance and their good state of preservation, were among the first fossil forms to be described from this coast. They all belong to the Clypeastridæ, being distributed among the genera, *Echinarachnius*, *Scutella*, *Astrodapsis*, and *Clypeaster*. The species have generally been referred to the geological periods as follows:

Quaternary—*Echinarachnius excentricus*, Esch.

Pliocene
- *Echinarachnius excentricus*, Esch.
- *Scutella interlineata*, Blake.
- *Astrodapsis Whitneyi*, Rém.
- *Astrodapsis tumidus*, Rém.

Miocene
- *Astrodapsis tumidus*, Rém.
- *Astrodapsis Antiselli*, Con.
- *Scutella* (*Clypeaster*) *Gabbi*, Rém.
- *Echinarachnius* (*Scutella*) *Gibbsi*, Rém.
- *Clypeaster ?* (*Echinarachnius*) *Brewerianus*, Rém.

From the observations of the writer it appears that the geological classification of these species, as indicated above, may not be accepted without certain modifications, which are dependent on the local classification of Neocene formations. In order to discuss the subject intelligently it will be necessary first to notice briefly the occurrence of the species individually.

OCCURRENCE AND RANGE OF SPECIES.

Echinarachnius excentricus and *Scutella interlineata* are both found in the sea cliffs of Seven-mile Beach, south of San Francisco, which have been referred to the Merced series (Pliocene). There the first-named species occurs near the top of the section. If the upper fossiliferous beds of the Seven-mile Beach section are Quaternary, as many of the writers on the palæontology of this series (Rémond*, Gabb†, Ashley‡) have suggested, it will probably be shown that *E. excentricus* does not occur there below the base of

* Geol. Surv. of Cal. Geology, Vol. I, p. 79.

† Geol. Surv. Cal. Palæontology, Vol. II, p. 110.

‡ Proc. Cal. Acad. Sc., Second Ser., Vol. V, p. 330.

the Post-pliocene. It is not impossible, however, that it belongs also to the top of the Pliocene, since the line drawn between the Quaternary and the Pliocene near the top of the cliff section is to some extent an arbitrary one.

Besides the occurrence at Seven-mile Beach, *E. excentricus* is known from the Quaternary of Santa Barbara and San Pedro and also from San Fernando, Los Angeles County. At the last-named locality it is said to be in the Pliocene. Satisfactory information regarding these occurrences has not been obtained by the writer, but, judging from the state of preservation of the specimens examined, they are all either of late Pliocene or of Quaternary age.

Scutella interlineata is fairly common throughout the greater portion of the Merced. It is not rare near the base of the series at the typical locality, on Seven-mile Beach, and is found at intervals up to a point considerably beyond the middle of the section. It is known also from Humboldt County, California, where it is associated with a fauna similar to and probably of the same age as that of the lower portion of the Merced near San Francisco.

The remaining species which have been considered as Pliocene, viz., *Astrodapsis Whitneyi* and *A. tumidus** occur along with *Scutella* (*Clypeaster*) *Gabbi* in a series of strata which is well developed on the south shore of San Pablo Bay, at Kirker's Pass north of Mt. Diablo, and in the hills to the south and west of Mt. Diablo. At these places they are associated with a fauna not known at other horizons, containing among other characteristic forms, *Pseudocardum Gabbi*, *Pecten Pabloensis*, *Pinna Alamedensis*, *Mulinia densata*, *Trochita* n. sp., *Littorina Remondi*, and *Trophon ponderosum*.

Within this series the *Scutella*, wherever present, occupies a lower horizon than *Astrodapsis*. In a remarkably well-exposed cliff section, near the Union Oil Refinery, on the south shore of San Pablo Bay, the best-known example of the zonal distribution of these sea-urchins is very clearly shown. At this point the strata are standing almost vertically, exposing a thickness of nearly

* *A. tumidus* occurs also in the southern part of the state, in Santa Barbara and Ventura Counties.

fifteen hundred feet. At the bottom or north side of the section *Scutella* is very abundant and *Astrodapsis* is absent. Two or three hundred feet farther up *Scutella* disappears and *Astrodapsis* appears. From that point to a distance of nearly one thousand feet higher *Astrodapsis* is abundant, *Scutella* apparently not passing beyond the stratum at which *Astrodapsis* appears. The two species are, however, abundant in beds less than ten feet apart, and may be found to overlap. At other localities in this formation the same sequence of genera was observed. The exact relations which the two species of *Astrodapsis* bear to each other in time have not yet been determined, but *tumidus* is possibly the older. The *Astrodapsis* forms are perhaps the more characteristic of the formation, as the lower beds with *Scutella* are sometimes absent, while the upper and much thicker *Astrodapsis* beds are usually present.

The third species of *Astrodapsis*, viz., *Antiselli*, which has been supposed to be Miocene, is possibly identical with one of the other two forms. It occurs* in San Luis Obispo and Kern Counties, where it is associated with a fauna much like that found with *A. tumidus* and *Whitneyi*.

Of the remaining forms referred to the Miocene, *Echinarachnius* (*Scutella*) *Gibbsi* is known from Neocene strata, near Buena Vista Lake, Kern County.† It is also listed by Ashley‡ from his transition beds near Santa Cruz, where it is said to be associated with *S. interlineata*.

The oldest of the Neocene sea-urchins, *Clypeaster?* (*Echinarachnius*) *Brewerianus* is a common species in the upper portion of a voluminous series in Contra Costa County, generally recognized as Miocene, which at Walnut Creek, near Mt. Diablo, underlies the formation containing *Astrodapsis*.

From what has already been stated, regarding the distribution of the Neocene and Quaternary Echini, it will be seen that there are, in the middle Californian region at least four distinct sea-urchin horizons above the middle of the Miocene. The zone

* Pacific R. R. Rep., Vol. 7, p. 196.

† Proc. Cal. Acad. Sc., Vol. III, 1863–67, p. 13. Rémond.

‡ Proc. Cal. Acad. Sc., Second Ser., Vol. V, p. 328.

of *Clypeaster?* (*Ech.*) *Brewerianus*, in the upper portion of the Miocene of Contra Costa County, is the lowest. That of *Echinarachnius excentricus*, in the Quaternary, perhaps including the latest Pliocene, is the highest. Between these lie the zone of *Scutella interlineata*, in the Merced series, immediately below the Quaternary of Seven-mile Beach, and the beds with *Astrodapsis* and *Scutella* (*Clypeaster*) *Gabbi*, above the recognized Miocene of Contra Costa County.

Both of these last-mentioned, intermediate horizons are generally referred to the Pliocene, though the age of both has been variously determined by different investigators. It is thought that the distribution of their characteristic sea-urchins and the associated molluscan forms throws some light on the question of their relative age.

THE SAN PABLO FORMATION AND ITS GEOLOGIC RELATIONS.

The series of strata characterized by the presence of *Astrodapsis* and *Scutella* (*Clypeaster*) *Gabbi* may, with reference to its more important features, be treated as a distinct formation, and will be referred to in this paper as the *San Pablo Formation.*

Faunal and Lithological Characters of the San Pablo.—At all of the localities at which the San Pablo is known, it is characterized faunally by the presence of a peculiar assemblage of genera and species, in which *Astrodapsis* is the most abundant and easily recognized form. The fauna is known so far by about fifty species, of which nearly one-third are peculiar to these beds, about one-fourth are known also from the Contra Costa County Miocene, and one-sixth from the Merced. A little less than one-half of the known forms are extinct. The number of species made use of in this calculation is, unfortunately, not large, but the proportions have been about the same in all of the collections made at different localities by Gabb, Turner, and the writer, so that we may consider them as approximately indicating the relations of the *most vigorous* part of the then existing fauna to that of the nearest periods.

The sea-urchins form the most prominent organic feature of

the formation, neither of the *Astrodapsis* species being found outside of it. The zone of *Scutella* (*Clypeaster*) *Gabbi* is not always present, but may be considered as belonging to the formation.

Lithologically, and even scenically, the strata of this formation are readily distinguished from those of the adjoining groups. A considerable thickness of tuffs and ashes, most prominent in the upper portion of the formation, and the peculiar weathering of the sandstones, are constant and striking characters of the greatest value in working at points where fossil remains are rare or absent.

Relation of San Pablo to Contra Costa County Miocene.—The relations of this formation to the Contra Costa County Miocene are well shown at Walnut Creek, where the highly disturbed Miocene-bearing *Clypeaster?* (*Ech.*) *Brewerianus*, is accompanied by the Astrodapsis-bearing beds, standing at the same angle and seemingly conformable on it. *Scutella* (*Clypeaster*) *Gabbi* has not been seen at this point, though it may be present below the *Astrodapsis* beds. It is known, however, on the opposite side of the valley, where it seems to be low down in the formation.

At San Pablo Bay the beds bearing *Astrodapsis* and *Scutella* form a wide syncline, the bottom of which is the *Scutella* zone. On this lie the *Astrodapsis* beds with tuffs and ashes above. The northern limb of the syncline, resting on the upper portion of the Contra Costa County Miocene, is in almost vertical position. On the southern side of the syncline the strata stand at a much lower angle, about twenty-five degrees.

Though no distinct unconformity between the lower portion of the San Pablo and the Contra Costa County Miocene has been seen, a break is indicated at several localities. At present it is not possible to draw a sharp line between the two formations at all localities. Where ash and tuff beds are present in the lower portion of the San Pablo the separation is easily made.

Relation of San Pablo to Merced.—The stratigraphic relations of the San Pablo to the Merced are not yet definitely known; the two formations, though occurring only a few miles apart, have not yet been seen in contact.

Faunally the San Pablo does not appear to be as closely

related to the Merced as it should be if the two belong to the same formation or the same period, it is in fact not so closely related to the Merced as to the Contra Costa County Miocene. At San Pablo Bay the formation shows more than one thousand feet of very fossiliferous sandstones containing an abundance of echinoids, all of which are different from those of the Merced. The Merced section south of San Francisco shows several thousand feet of fossiliferous sandstones with echinoids but not a single specimen of any of the San Pablo species has been found among them. The molluscan faunas of the two formations, though not mutually so exclusive as the Echinoderms, are very different. Not more than one-fifth of the fifty species known from the San Pablo occur in the Merced. It is difficult to conceive of any way in which two shallow-water, marine faunas so different as these could exist within a few miles of each other, through the length of time required in forming more than one thousand feet of sandstones, without their becoming mingled to some extent, and mingling of their most characteristic forms we do not find.

So far as faunal proof is concerned, it is not easy to believe that the Merced and San Pablo have been deposited at the same time, and any stratigraphic evidence which may later tend to indicate their contemporaneity will show the existence of biological conditions in Middle California, during that period, radically different from any which have ever been met with elsewhere.

Age of San Pablo.—If the Merced and San Pablo are not of the same age, both faunal and stratigraphic evidence would point toward the latter as the older of the two. The fauna of the San Pablo is more closely related to that of the Miocene of Contra Costa County than to the Merced fauna. Stratigraphically the formation shows a much greater amount of deformation than the Merced, and where the upper beds are overlaid by the Quaternary a much more pronounced unconformity is seen than has so far been shown to exist between the Merced and the Quaternary. Lithologically there is a noticeable difference between the two, as the great beds of ash and tuff so characteristic and widespread in the San Pablo appear to be entirely absent from the Merced. The only distinctly volcanic deposit in the whole cliff section at Seven-

mile Beach is a thin layer of ash, about two hundred feet above the most fossiliferous Quaternary horizon.

The San Pablo formation has been called Miocene by Conrad* and Gabb† where it is exposed on the shore of San Pablo Bay, Miocene by Gabb‡ at Walnut Creek, where it contains the same fauna and shows the same sequence of beds, and Pliocene by Gabb§ at Kirker's Pass, to the north of Mt. Diablo, where the beds are indistinguishable faunally, lithologically, and otherwise from those at Walnut Creek. It appears then that at different localities the same formation has been referred to different periods.

The Merced series was determined as Pliocene by Rémond,‖ Gabb,¶ and Lawson,** has been considered by Ashley†† as mainly Pliocene, but probably including also some Miocene, while Lindgren‡‡ has recently suggested that it may be correlated with the Pleistocene of the Sierra Nevadas.

If the Merced series be Pliocene, the San Pablo must be below the upper Pliocene at least. It has already been shown to rest above what has been considered Miocene in Contra Costa County. In other words, it probably represents middle Neocene. Such a determination of the age of this formation, it will be noticed, was, to some extent, foreshadowed by the reference of different localities on the same beds indifferently to the Miocene or the Pliocene, by the earlier writers on the Geology of this region.

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* Pacific R. R. Rep., Vol. VI, pp. 69, 71.

† Geol. Surv. of Calif. Palæontology, Vol. II, p. 109.

‡ *Ibid.*, p. 2.

§ Geol. Surv. of Calif. Geology, Vol. I, p. 31.

‖ *Ibid.*, p. 79.

¶ Geol. Surv. of Calif. Palæontology, Vol. II, p. 110.

** Bull. Geol. Deptm. Univ of Calif., Vol. I, p. 143.

†† Proc. Calif. Acad., Second Ser., Vol. V, p. 312.

‡‡ Jour. Geol., Vol. IV, p. 905.—As far as the relative ages of the horizons are concerned, Mr. Lindgren's correlation may be correct. This does not, however, by any means necessitate the reference of the Merced to the Pleistocene, as its marine fauna, which has generally been taken to indicate late Tertiary age, really furnishes more data of value in age determination than could be obtained from the fresh-water formations of the Sierra region.

CLASSIFICATION OF THE NEOCENE OF MIDDLE CALIFORNIA.

The following table, giving the occurrence and geological range of the echinoid species known above the middle Neocene, illustrates the faunal and the probable time relations of the formations in which they occur to each other.

Quaternary—*Echinarachnius excentricus*, Esch.

Merced	*Echinarachnius excentricus* Esch. (?) *Scutella interlineata*, Blake.
San Pablo	*Astrodapsis Whitneyi*, Rém. *Astrodapsis tumidus*, Rém. *Scutella* (*Clypeaster*) *Gabbi*, Rém.
Contra Costa County Miocene	*Clypeaster?* (*Echinarachnius*) *Brewerianus*, Rém. *Echinarachnius* (*Scutella*) *Gibbsi*, Rém. (? ?)

The Contra Costa County Miocene represents a large portion of the Lower Neocene. Whether it includes all of the Miocene is uncertain. The Merced certainly includes a large portion of the Upper Neocene, but how much is not yet determined. The San Pablo probably represents middle Neocene. It may be found to fall principally within the limits of the Miocene, and probably does not represent a very large portion of the Pliocene. The more exact correlation of these horizons with the Neocene periods of eastern United States and Europe can be accomplished only when our knowledge of the Tertiary faunas of the Pacific Coast is much more complete than at present.

The intercalation of the San Pablo formation between the Contra Costa County Miocene and the Merced Pliocene adds to the already long Tertiary era of California a period of sedimentation, during which at least fifteen hundred feet of strata were deposited. The thickness of the Tertiary section and the number of physical and organic changes, which took place in that era on the Pacific Coast, indicate that the general tendency has been to underestimate rather than overestimate the relative length of Tertiary time.

CORRELATION OF THE AURIFEROUS GRAVELS WITH THE COAST RANGE NEOCENE.

For a number of years the relation of the auriferous gravels of the Sierra Nevadas to the marine deposit of the Coast Ranges has furnished one of the most important problems in Californian geology. The correlations that have so far been made have been based largely on comparisons of fossil plants. The plant remains from the Coast Ranges, which have been made use of in these correlations, have been obtained at Kirker's Pass, the Railroad Ranch on the western slope of Mt. Diablo, and Corral Hollow near Livermore Pass. The specimens from Kirker's Pass and Railroad Ranch are from the *San Pablo formation.* Part of those from Corral Hollow are in a peculiar matrix not known to the writer outside of the San Pablo. The flora is much the same at all three localities. To this flora that of the auriferous gravels shows a considerable degree of relationship. It is probable that the difficult problem of the more exact determination of the age of the auriferous gravels will be most satisfactorily solved through comparison of their flora with that of the San Pablo formation.

University of California, May, 1898.

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THE GEOLOGY OF POINT REYES PENINSULA

BY

F. M. ANDERSON

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INTRODUCTION.

General Statement.—One peculiarity of the western coast of the United States south of Puget Sound is the comparatively unbroken regularity of its shore-lines. Few islands or inlets fringe the continental border for many hundreds of miles, and the student of geology here does not often have the advantages of a much-dissected coast.

The coast of California furnishes at least a few exceptions to the rule, among which may be enumerated the peninsula of Point Reyes. This body of land is almost severed from the mainland in a manner that at once challenges the attention. It is roughly triangular in outline, about sixty-five square miles in area, and lies some thirty miles north of San Francisco and the Golden Gate.

The study of its geology was undertaken at the suggestion of Professor Lawson, to whom we are indebted for much that is known of the physiography of the coast of California. The field offers some unusual advantages for the study of the oscillatory movements that have affected the coast in Neocene and later times, the records of which are preserved in terraces and marine deposits. It embraces also the northern termination of a granitic massif that follows the coast in a series of ranges for more than two hundred miles. The relationship of these granites to others of remoter portions of the coast, for example those of the Klamath Mountains and of southern California, has not yet been ascertained and would richly reward investigation.

It is probable that many of the movements that have disturbed the region west of the great valley of California have had direct reference to this granitic axis, which has accordingly, therefore, been implicated causally in many of the structural phenomena of the Coast Ranges.

The relation of the geology of Point Reyes to these questions is direct, and it is regretted that a more complete treatment of them is beyond the scope of the present study. At best only a few suggestions can here be made.

The peninsula embraces more territory than is covered by the study represented in this paper, and more than is locally understood by the term.

Boundaries.—There is little difficulty in defining the boundaries of the field. The western border of the peninsula forms a long and gentle curve concave toward the ocean, extending north and south for about twenty miles. Its eastern boundary is mainly formed by the shore of Tomales Bay, a long and narrow inlet extending in a southeast direction for almost twenty miles. This bay, which is hardly a mile in width at any point, occupies a portion of a singular rectilinear depression that continues beyond the limit of tide-water in a low valley until it meets the axis of Baulinas Bay twelve miles to the southeastward. The low ground of this depression forms the neck of the peninsula, but as this territory was not all included in the present examination, the remainder of the eastern boundary was drawn at Bear Valley, which extends in a southerly direction to the ocean from near the head of Tomales Bay. The southern boundary of the field is formed by the shore of Drake's Bay, which describes a broad curve open toward the south. From the northern limb of Drake's Bay a system of shallow inlets extends for four or five miles toward the heart of the peninsula like the outspread fingers of a great hand. This system of inlets is locally known as Lamenteur Bay, and on the charts of the Coast and Geodetic Survey, Drake's Estero. The peninsula as thus outlined is almost an equilateral triangle, with its southern and western sides somewhat gently curved.

Literature.—Whitney mentions[1] in his report published in 1865, occurrences of granite and white slate on the peninsula of Punta de los Reyes, and speaks also of crystalline limestone and schists, and of the well-marked depression occupied by Tomales Bay, the valley of Arroyo Olemus Lake, and the Bay of Baulines.

[1] Geological Survey of California, Vol. 1, pp. 84–5.

The work of the State Survey, however, was too brief and widely distributed to give to this section more than a passing notice.

Following this brief description and the little information to be gathered from the reports of the Coast and Geodetic Survey, the State Mining Bureau in its geological map of the state shows only approximately the distribution of the formations on this portion of the coast.

In 1894 Professor Lawson, on a tour along the northern coasts of California, visited the peninsula, and has discussed[1] some of the more important matters of its physiography. The field-work for the present paper was done at intervals in the winter of 1896–7. Its writing and the necessary laboratory study was done meanwhile at the University of California with the advice and assistance of Professor Lawson.

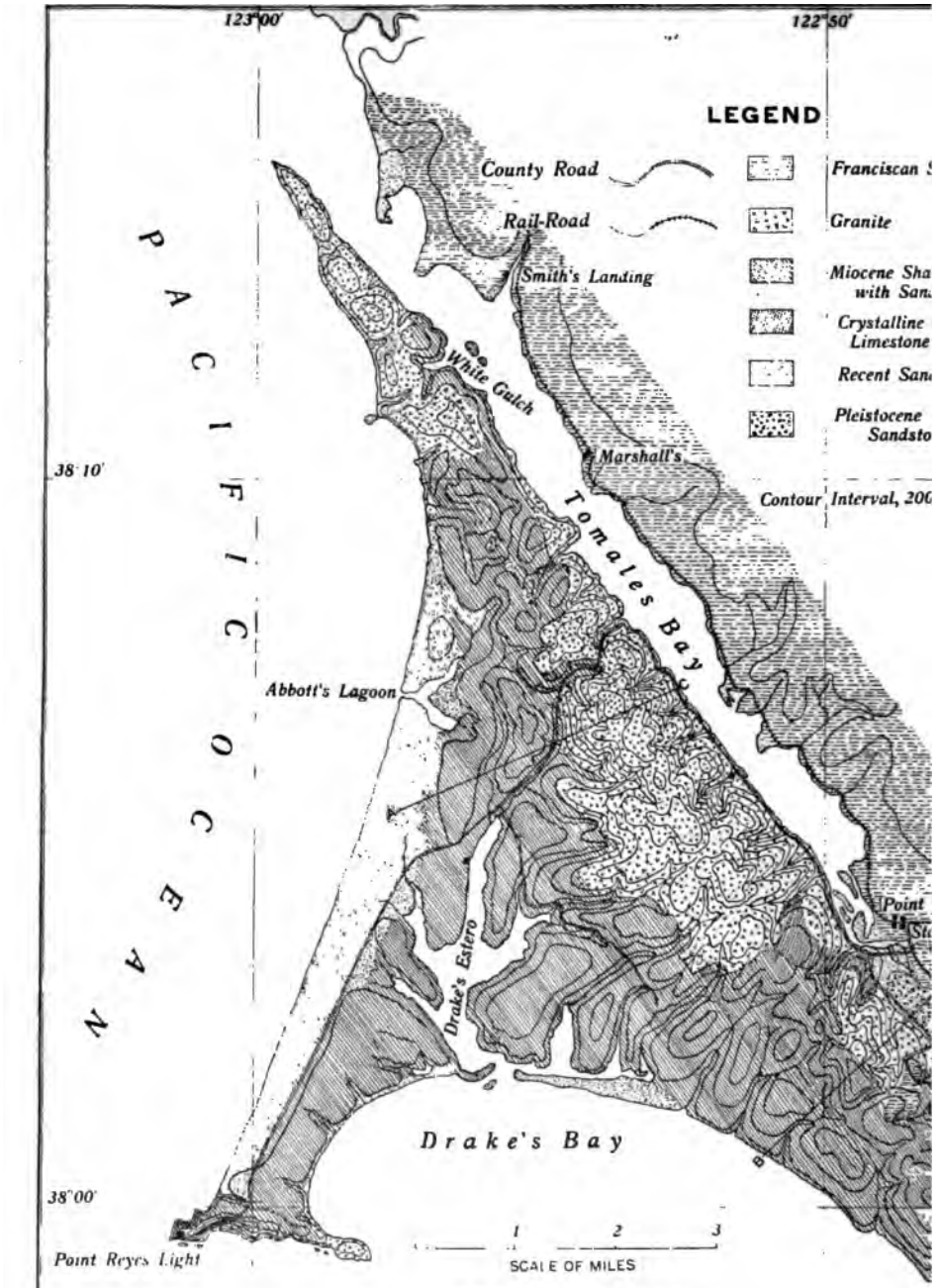
GRANITE.

There are not many distinct formations occurring on the portion of the peninsula covered by this work, which are of large areal extent. The more important of them are the granites and the Miocene sedimentary series. But besides these there are some smaller areas of metamorphic limestone and quartzites, with a few patches of schists, and some recent deposits of coarse alluvial detritus and of æolian sands.

Areas.—Granite occurs upon the peninsula in three areas, two of which are more or less connected although they show some general petrographic differences.

At the northern extremity granites occupy almost the whole of the ridge from Tomales Point southward for a distance of about five miles. Here they are overlain by the Miocene deposits and patches of drifted sands. At White Gulch, on the Pierce Ranch, the granite is covered by a moderate thickness of yellowish sandstone and white shale. Northward the cliffs on both sides of the point are almost wholly of granite. Southward on the ocean side, opposite the Skinner Ranch, the granite hills of the long, narrow point drop suddenly off southward to the level of a low terrace or rolling plain

[1] Bull. Dept. Geol. Univ. Cal., Vol. 1, pp. 245, 264.



GEOLOGICAL MAP

of

POINT REYES PENINSULA

by

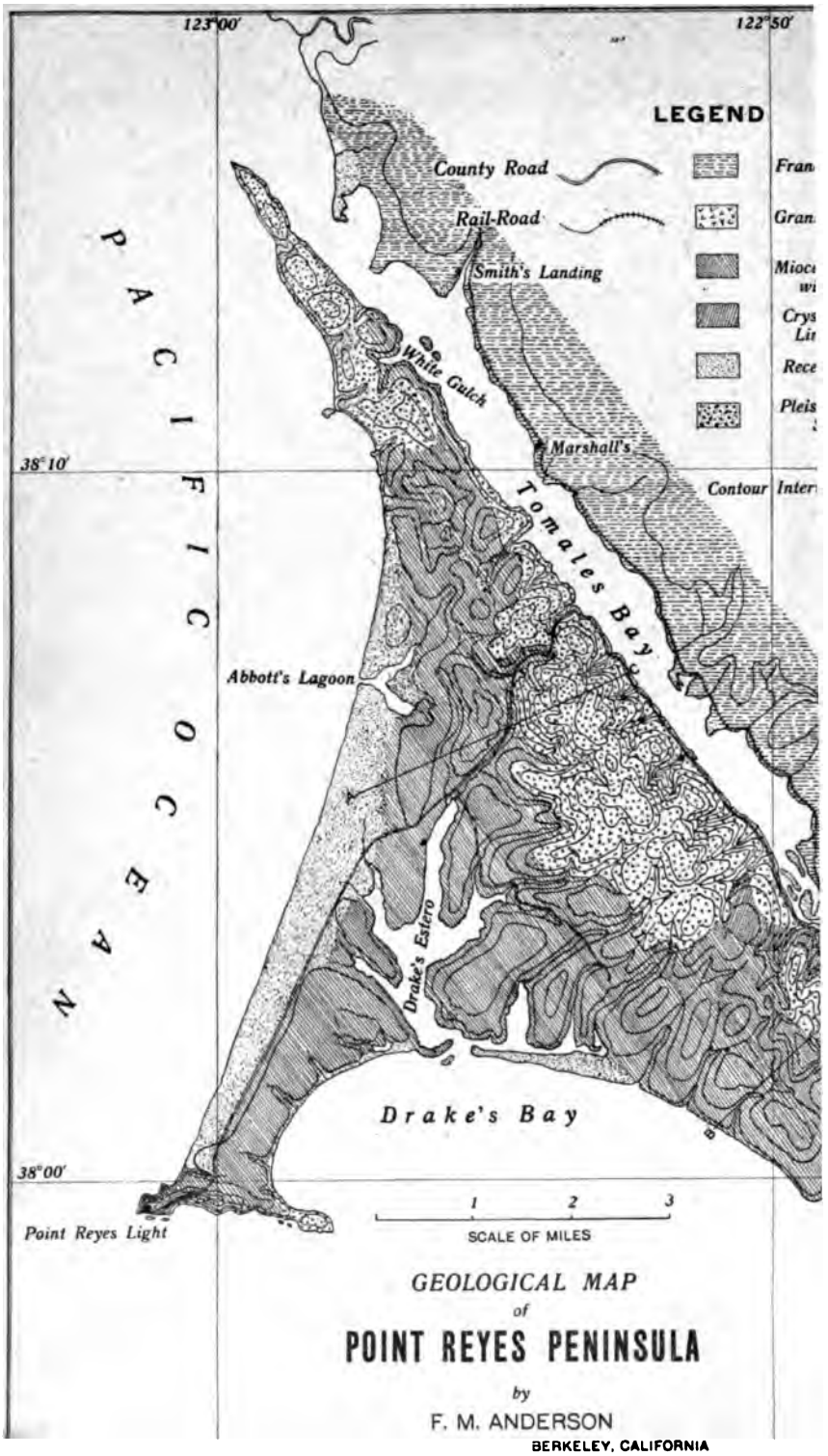
F. M. ANDERSON

BERKELEY, CALIFORNIA

underlain by Miocene sediments. No more granite is seen along the shore from this point southward, but along the bay they are only imperfectly covered. Along this side of the peninsula the granite comes to the surface and is more or less continuous with the second area of granite further south.

This second area, which forms the largest body of granite on the peninsula, lies west of the head of Tomales Bay. It embraces Vision Hill, and a large portion of Whittenberg Hill, with almost the whole of the ridge connecting them. From near the entrance of Bear Valley, the eastern margin of the granite follows the county road toward, and along the shore of the bay to the point, at which the road turns westward through the hills. Here it is interrupted, for a few hundred yards only, by an exposure of thin-bedded siliceous schist, which rests upon the granite at the water's edge. Northward, beyond this point, the granite is exposed along the shore for several miles. Along the western flanks of the ridge which follows the shore of the bay the Miocene sediments overlie the granite, and make its western boundary much less regular. The area widens gradually, however, from the north, where it is less than a mile in width, until at a point opposite the head of Tomales Bay, its greatest width is a little more than three miles. Scattered patches of sedimentary rocks cover the northern portion of this area. A tongue of these sediments occupies the depression to the north of Vision Hill, while the bold spurs of the hill farther to the south extend the granite westward into the border of the Miocene rocks. The most southern exposure of granite belonging to this area that was observed, was on the eastern brow of Whittenberg Hill, opposite the hamlet Olema.

The third area of granite is distinct and entirely separated from the preceding two, at least superficially, by the sedimentary rocks of the Miocene in the lowlands surrounding Drake's Estero. This area of granite is at the extreme southwestern promontory of the peninsula. It is smaller than either of the other two areas, and forms only a narrow ridge extending in an east and west direction for about a mile and one-half. It has a general elevation of about five or six hundred feet, though at its eastern end it drops somewhat lower than this. The southern face of this ridge is a precip-



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BERKELEY, CALIFORNIA

underlain by Miocene sediments. No more granite is seen along the shore from this point southward, but along the bay they are only imperfectly covered. Along this side of the peninsula the granite comes to the surface and is more or less continuous with the second area of granite further south.

This second area, which forms the largest body of granite on the peninsula, lies west of the head of Tomales Bay. It embraces Vision Hill, and a large portion of Whittenberg Hill, with almost the whole of the ridge connecting them. From near the entrance of Bear Valley, the eastern margin of the granite follows the county road toward, and along the shore of the bay to the point, at which the road turns westward through the hills. Here it is interrupted, for a few hundred yards only, by an exposure of thin-bedded siliceous schist, which rests upon the granite at the water's edge. Northward, beyond this point, the granite is exposed along the shore for several miles. Along the western flanks of the ridge which follows the shore of the bay the Miocene sediments overlie the granite, and make its western boundary much less regular. The area widens gradually, however, from the north, where it is less than a mile in width, until at a point opposite the head of Tomales Bay, its greatest width is a little more than three miles. Scattered patches of sedimentary rocks cover the northern portion of this area. A tongue of these sediments occupies the depression to the north of Vision Hill, while the bold spurs of the hill farther to the south extend the granite westward into the border of the Miocene rocks. The most southern exposure of granite belonging to this area that was observed, was on the eastern brow of Whittenberg Hill, opposite the hamlet Olema.

The third area of granite is distinct and entirely separated from the preceding two, at least superficially, by the sedimentary rocks of the Miocene in the lowlands surrounding Drake's Estero. This area of granite is at the extreme southwestern promontory of the peninsula. It is smaller than either of the other two areas, and forms only a narrow ridge extending in an east and west direction for about a mile and one-half. It has a general elevation of about five or six hundred feet, though at its eastern end it drops somewhat lower than this. The southern face of this ridge is a precip-

itous ocean cliff for its whole length. The Point Reyes Light stands at its western terminus. At the beach, below the government dwellings, is the most western exposure of the granite. It is here overlain by massive beds of conglomerate, but it rises from beneath these to the summit a little farther to the east, and then forms the remaining three-fourths of the sea-cliff extending eastward. This narrow strip of granite does not exceed a width of a few hundred feet, except at its eastern end, where it juts into Drake's Bay. This projecting headland is of granite, and from this a narrow strip of granite follows the shore of Drake's Bay northward for half a mile. It is then replaced by beds of very coarse conglomerate and sandstone.

Petrographic Character.—In the field the granites of Point Reyes appear as moderately coarse-grained, light gray rocks showing rough and rounded surfaces where they are firm, though usually they are much decomposed. Where erosion is not rapid the rocks are decayed, often to a depth of a dozen feet or more, but on the summits where harder phases protrude, and in the deep ravines where the erosion is greatest, and along the shore the rocks are firmer and often more angular. All of them, where favorably exposed, are seen to be greatly shattered and broken, and testify to the large amount of disturbances they have undergone. The rock is mostly unfit for quarrying purposes on this account, since it is not easy to find many blocks of any considerable size.

Veins of aplite occur, and are not uncommon, along the eastern side of the peninsula and at its northern extremity. Pegmatitic rock is sometimes found which, occasionally, is very coarse-grained. These granites are to be classified as normal biotite granites. Quartz is in only moderate proportions, and both orthoclase and plagioclase feldspars are present. As to the quantity of biotite present, there is considerable variation. Basic segregations are common, in which there is no quartz and little feldspar, while on the other hand there are phases containing but little biotite. Hornblende is not abundant, or, rather, it is almost entirely absent.

There are three prevailing types of granite, one of which is confined to the southwestern area, and one almost wholly to the northern.

One common type is a moderately coarse-grained rock in which biotite is so conspicuous as to give it a decidedly dark color. Orthoclase is abundant, though not the prevailing feldspar. Plagioclase, approaching oligoclase, predominates, twinned commonly on the albite law, while the pericline law is not infrequent. The plagioclase has the most marked idiomorphic tendency of the constituent minerals. Quartz appears in the sections as rather large allotriomorphic plates, very irregular in shape.

Another type is similar to this in its composition, but the quantity of biotite is reduced to a very subordinate amount. This rock is more compact, finer grained, and lighter in color than the other, and better resists weathering. This is more common at the northern angle of the peninsula. "Mussel Rock," on the beach west of the Pierce Ranch, is of this variety. It stands out in the ocean, almost entirely severed from the mainland of the Point. The rocks in this vicinity show a tendency to segregation into basic and acid zones. Veins of aplite are frequent here, cutting the rocks in various directions. Still, the most common type of granite on Tomales Point is the coarser one, in which biotite forms a conspicuous proportion.

The most common accessory mineral here is titanite. It occurs in large idiomorphic crystals, some of which are one-fourth of an inch in length, or even larger.

Magnetite is common along with chlorite, both of which seem to have resulted from the alteration of brown biotite. This alteration has resulted in the wedging apart of the cleavage plates of the biotite, producing an interlocked structure of the biotite and the chlorite. The chlorite is strongly pleochroic in sections, showing the basal cleavage, but in sections parallel to the cleavage it is almost isotropic. Narrow bands and scattered scales of chlorite are common in some of the sections. The feldspar contains many inclusions of hornblende and biotite.

The granites of the larger area are more varied in their character than those of the northern area. The rocks are not so well exposed, since they have no ocean cliffs, and are more thickly covered by underbrush, which protects them from erosion. Yet in

the deeper cañons and on some of the high ridges, one is able to find firm rock, though not often fresh rock.

At the two higher and southernmost summits of Vision Hill the granite is coarse-grained and dark, with a large amount of biotite, and occasionally large crystals of feldspar and quartz. At the northern and lower summits the texture of the rock is more uniform and of a finer grain. It has here been pressed and broken into a columnar appearance, consisting of large, roughly cubical blocks. At one of the northern summits the rock is peculiar from the large amount of magnetite which it contains, seemingly as an original mineral. It is a fine-grained rock, containing both orthoclase and plagioclase, with quartz, hornblende, and biotite. The biotite has been altered to chlorite to a limited extent. The mass may be only a large secretion from the granite, in which there is an unusually large proportion of iron oxide. At the head of Tomales Bay the rock exposed in the road-cuts is a dark gray granite, with zones of basic rock, and with veins of quartz and aplite. One slide of this rock shows a large crystal of titanite, though it does not seem to be common here. All the rock contains iron oxide and shows the alteration of biotite to chlorite. At the western base of the ridge occupying this area the rock is compact and resists weathering more perfectly. In other respects it is similar to that just described. The pericline law in the twinning of the feldspars is frequently noticeable.

A third type of granite is that of the southwestern angle of the field. It is essentially similar in composition though physically different from that of the other areas. This granite is of the porphyritic type, similar to that described by Professor Lawson[1] from near Monterey. It is of uniform character throughout, the rather fine-grained ground-mass consisting of a compact aggregate of quartz, orthoclase, and plagioclase with no large amount of biotite. In fresh surfaces it has a characteristic vitreous appearance. The phenocrysts are large crystals of pink orthoclase, varying in size from one-fourth of an inch to two inches in length. They are mostly twinned on the carlsbad law, though

[1] Bull. Dept. Geol. Univ. Cal., Vol. 1, pp. 9–15.

this is not always to be seen. As far as was observed no parallel orientation could be noticed in these crystals, as is sometimes the case in the Monterey granites. Orthoclase is much more abundant in these rocks, as well as quartz, though plagioclase is the dominant feldspar. As a rule, the rocks of this area are less broken and more resisting to the weather than those of the other areas. Aplites and basic segregations are not common. Veins of calcite were seen at several points penetrating the rocks. Usually they were of only an inch or more in thickness.

There is yet one other occurrence of granitic rock so peculiar in its character that it deserves mention. It belongs to the larger area, and occurs near its southeastern boundary in a cañon west of Olema. It resembles, at first glance, a partially decomposed aplite, and was at first taken to be such. Further study of it showed, however, that its peculiar appearance was due to a complete and very thorough crushing it had undergone.

It occupies a zone of more than half a mile along the cañon, with a width of at least one or two hundred yards. It is perhaps a fault breccia. Under the microscope it shows angular fragments of quartz and feldspar cemented together in a matrix of pulverulent and partially kaolinized material containing some calcium carbonate. Both orthoclase and plagioclase fragments are plentifully distributed through the mass along with quartz, and all of them are very much cracked and shattered. Few traces of biotite or any dark mineral are to be found in it. It lies in the midst of a system of intersecting faults, and serves to indicate how great the disturbances of this district have been.

In most of the granites of the peninsula the more transparent minerals show an undulous extinction when turned between crossed nicols. This is very noticeable in the rocks of Tomales Head, both in the quartz and in the orthoclase and even in the plagioclase. In the rocks of Vision Hill it is even more conspicuously seen, while at the southwest angle of the field it is apparent only in the quartz and orthoclase. All the larger crystals show a large amount of fracturing, and irregular cracks are very abundant. This still farther shows the great stress to which the rocks have been subjected.

Endomorphism of the Granite.—The relation of the granite of the peninsula to other formations will be more fully stated in the succeeding paragraphs, yet it may be incidentally referred to here for the fuller discussion of the granite itself. Lacroix has described the occurrence in the Pyrenees of an acid biotite granite which has been intruded into a series of calcareous and siliceous sedimentary rocks. Among the metamorphic alterations effected in the zone of contact was the development of more basic phases in the granite itself where it was found in contact with limestone. Quite similar relations are to be seen on the peninsula. Immediately beneath a zone of crystalline schist developed in the sedimentaries is a zone of granite different from any other that was found in the field. A thorough study of this interesting occurrence was not undertaken, although there can be no doubt that it would be well rewarded.

The character of the granite at this contact is not uniform. It seems, in fact, to be quite variable. Much of it is a very dark, rather fine-grained, hornblende-bearing rock, containing only a little quartz and not a large amount of feldspar. The hornblende is of the green variety and considerably more abundant than the dark grains of biotite. The feldspars are similar to those of the normal granite in which orthoclase predominates. Oligoclase is common and andesine is occasionally seen. These are the only idiomorphic elements found in the rock. Magnetite occurs in scattered grains resulting apparently from the alteration of hornblende. Another phase of the granite which is perhaps less basic than this is a light-colored garnetiferous variety which contains no hornblende and a smaller amount of biotite than most of the normal granite. In other respects it may rank with the normal variety, except that it contains great numbers of small pinkish-colored garnets resembling some of the lime-iron varieties. This rock was found not far from the preceding variety below the zone of crystalline schist. Other basic phases are common but were not sufficiently studied to make definite statements in regard to them.

Relation to Other Massifs.—The geological relation of the granites of the Coast Ranges of central California to those of other parts of the state, or of the coast, is a very interesting question.

Too little is yet known for any satisfactory comparison, but it is worth while to record a few observations upon this topic which may be in the line of reaching some conclusion. Granites have been more or less perfectly described from several points in western California south of the area of Point Reyes peninsula, as, for example, from Montara Mountain,[1] Monterey and Carmelo Bays,[2] and from near San Luis Obispo,[3] with the exception of some of the "Montara granite," which Professor Lawson calls a hornblende-biotite granite. All the types yet described are rather acid rocks in which biotite is the dominant fero-magnesian mineral. Quartz is generally abundant and the feldspars are both orthoclase and plagioclase. It is a remarkable fact that the porphyritic type with large phenocrysts of orthoclase, twinned on the carlsbad law, characterize three of the four regions thus far studied. This type has been well described from the vicinity of Monterey by Professor Lawson. In many respects this occurrence is paralleled by the porphyritic facies, if it may be so called, that occurs at the southwest angle of the Point Reyes area. Dr. Fairbanks mentions the same character as belonging to some of the granite near San Luis Obispo. The most common accessory mineral, found plentifully in at least three of these localities, is titanite. Other characters more strictly chemical will doubtless be recognized in time which shall prove more satisfactorily the essential identity of these granites, but at present these features are noticeable and have more or less weight. Northward along the coast or from its near vicinity no granites of a similar nature have been described, though there is probably an equivalent and contemporary rock to be found in the Klamath Mountains. A coarse-grained, quartzose, biotite granite makes up a large part of the central core of the Trinity Mountains at the head of the south fork of Salmon River. This granite has been intruded into a series of Paleozoic sedimentary, and older schistose rocks mentioned in another paragraph. The porphyritic character has not been noticed there, but further northward in the Siskiyou Mountains a similar granite occurs at Ashland peak and eastward,

[1] 15th An. Rept. U. S. Geol. Sur., 1894, pp. 408–415.
[2] Bull. Dept. Geol. Univ. Cal., 1893, pp. 9–18.
[3] Jour. Geol., Sept.–Oct., 1898, p. 567.

in which orthoclase is very abundant in large crystals and carlsbad twins that make the rock decidedly porphyritic. Mr. H. W. Turner has described a "granite-porphyry" from the Sierras[1] of Butte County, California, that at first appears to resemble that of the Coast Ranges. It appears, however, for the most part to be confined to dikes, or at least already very limited. The phenocrysts are said to be of quartz and plagioclase. East of the Yosemite Valley and at other places in the Sierra Nevada[2] porphyritic granite occurs which bears a much stronger resemblance to that of the Coast Ranges. According to Professor Lawson[3] there is some resemblance between some of the granite of the Coast Ranges and the "granodiorite" of the Sierra Nevada. Writing of the rock from near Monterey he says: "The ground-mass of the rock certainly belongs to that intermediate type for which Becker has proposed the term *granodiorite*." Perhaps there is also some resemblance to be found in the hornblende-bearing facies of Montara Mountain.

On the whole, however, there appears to be something of contrast in the types most characteristic of the Sierras and of the Coast Ranges. Basic granites of the types common in the Sierras are not much known in the Coast Ranges, while on the other hand the acid biotite granites, such as have been described from the Coast Ranges, are relatively much less abundant in the Sierras. Yet too little is known of either region to make any general comparison either satisfactory or safe.

PRE-GRANITIC CRUST.

It seems a little remarkable that so few remnants of the ancient crust, into which the granites of the Coast Ranges arose, have been definitely recognized as such. There are traces of its rocks found in the conglomerates of the Tertiary and older periods in many places where such beds occur, but there are few, if any, extensive formations that have been clearly shown to have formed a part

[1] 17th An. Rept. U. S. Geol. Sur., pp. 572, etc.
[2] 14th An. Rept. U. S. Geol. Sur., pp. 478–480.
[3] Bull. Dept. Geol. Univ. Cal., Vol. 1, p. 15.

of this pre-granitic crust. At least two members of this ancient series have probably been recognized in this field.

Marble.—Immediately west of Point Reyes Station, upon the crest of the ridge, is a body of white, crystalline limestone which has at some time been used to a limited extent for making lime. It is almost pure white and highly crystalline. It contains numerous scales of graphite disseminated through it in clusters and patches. The best exposure of it is on the "old road" which crosses the summit from the head of Tomales Bay. The area is of limited extent and forms an irregular S-shaped body whose longer axis is not greater than one mile and whose width is perhaps one-fourth of a mile. It is the body of marble that was first described by Whitney as a feature of the peninsula.

The following is a rough analysis of a sample of the purer quality of it:—

$CaCO_3$	97.50%
$MgCO_3$	1.60"
Fe_2O_3	.35"
Insoluble residue	1.10"
	100.55%

This rock is similar to the white crystalline limestone of Montara Mountain mentioned by Professor Lawson.[1] It occurs also at Santa Cruz, and still more abundantly in the Santa Lucia Mountains, extending along the coast south of the Bay of Monterey.

Quartzite.—At the summit of one of the northern spurs of Vision Hill south of Inverness, there is an exposure of a very hard, dark gray, vitreous rock that under the microscope proved to be a fine-grained quartzite. The grains are small and rounded and closely crowded upon one another. They are quite clear, except that they contain a great many inclusions of iron oxide and other crystalline particles. Small fragments of both biotite and hornblende occur among the grains of quartz. No limestone or calcite was noticed in any connection with this rock, and no evidence of stratification was observed, though both of these might have been found, with sufficient searching.

[1] 15th An. Rept. U. S. Geol. Sur. 1895, p. 414, etc.

Crystalline Schists.—On another minor point of the summit was found a micaceous schist that evidently belonged to the same series, though it was not superficially connected with any other member. This rock is probably a representative of the "micaceous slate" mentioned by Whitney as occurring on the peninsula in some connection with the crystalline limestone.

On the shore of Tomales Bay, just north of the point at which the county road turns westward from the shore, there is a still more interesting exposure of rock that belongs with this series. In its general appearance it might be said to resemble a light-colored siliceous schist, and it may not be incorrect to so term it. It overlies the granite and extends along the shore of the bay for several hundred feet, dipping generally at an angle of about forty-five degrees toward the northeast. The bed is about thirty feet in thickness and is thoroughly crystalline. It consists of thin layers, ranging from one-fourth of an inch to more than an inch in thickness, which for the most part are alternating leaves of compact siliceous material and a mineral which qualitative and microscopic tests proved to be mainly wollastonite. The softer layers of the schist dissolve under the action of the weather and leave the siliceous portions standing in high relief. The siliceous part, which perhaps predominates in the exposure, is a fine-grained quartzite, very hard and vitreous, but not sharply separated from the intervening layers. Among the grains of quartz of which it is composed are scattered crystals of wollastonite. The grains of quartz are very irregular in shape and are apparently more or less corroded and encroached upon by granular masses of its associate mineral. Under the microscope the quartz grains are seen to be thickly sprinkled with small crystalline inclusions of high refractive power which were not identified. Some of them are hexagonal.

Wollastonite seems to be more abundant in the more siliceous portions of the schist, and in portions which contain less silica the wollastonite gives place to tremolite. When tremolite occurs it is in small lath-shaped crystals with an extinction angle generally below twenty-three degrees. It has no crystal terminations.

Age of Pre-granitic Series.—The pre-granite rocks of the peninsula deserve much more attention than they have yet received.

They constitute a remnant of probably the oldest formation in the Coast Ranges of this latitude. There can be little doubt that the series represented here by the limestone, quartzite, etc., is an equivalent not only of a similar group of associates found upon the San Francisco peninsula, but it is also a disconnected area of a terrane more extensive in parts of the Coast Ranges southward. In the Gavilan and Santa Lucia, if not also in the Santa Cruz Ranges, these limestones are conspicuous and have often been reared by orogenic action into prominent white peaks. The crystalline character, the clustered scales of graphite, their association with quartzites and crystalline schists and with granite, form thus far the strongest evidence of the identity of these metamorphic limestones which form the most important member of the series. Their age has been conjectural, yet the evidence, such as it is, points to a Paleozoic age. Paleozoic sediments of this character are more common on the Pacific Coast than those of any other era. Both at the north and at the south Paleozoic fossils have been found that throw the weight of presumption in favor of this determination.

In the Klamath Mountains metamorphic crystalline limestone of Devonian age is found extensively and is characterized by each of the above features, singularly enough.

In Siskiyou County graphite-bearing limestone indistinguishable from that of Point Reyes is found associated with vitreous thin-bedded quartzite, wollastonite schist, and granite. It is in that region, however, undoubtedly a continuation of the limestone occurring at Gazelle from which Devonian fossils have been obtained.[1]

LATER SEDIMENTARY ROCKS.

Franciscan Series.[2]—Near the southern boundary of the field, just west of Olema, and on the eastern slope of Whittenberg Hill, there is a small area of dark gray limestone that is thought to be the "foraminiferal limestone" of the San Francisco peninsula. It contains a large number of veins of white calcite varying in thickness from one-twelfth to more than one inch. The microscope

[1] Am. Jour. Sci., Vol. 147, pp. 416–422.

[2] Golden Gate Series of Fairbanks.

reveals no definite evidence of organic remains, and it is not certain that they are present. The rock has, however, the usual fetid odor of this limestone, and is associated with a hard, black shale that could well belong to the same series. These rocks seem to rest directly upon the granite, and are adjacent to the zone of crushed granite mentioned in another paragraph. This limestone is apparently a continuation of the foraminiferal limestone occurring a few miles to the southeast, where it has been quarried for lime.

This is the only body of this series of rocks that has been found within the boundaries of the field, though they occur abundantly just outside of it. The series occupies nearly the whole of the east shore of Tomales Bay, and extends to the southward along both sides of the valley, going toward Baulinas. The series, as a whole, seems not to have been greatly affected by the disturbances which have caused so many oscillations of the adjoining peninsula.

Miocene Sediments.—The Miocene series consists of three members, the upper two of which are not distinctly separated. The lower member is a dark, heavy conglomerate, in which the pebbles and stones range from one-half inch to more than one foot in diameter. The second member is a thin-bedded, cream-colored sandstone that passes quite gradually into the upper member, the special features of which will be described later. It is the white Miocene shale of the Monterey series, well known in the Coast Ranges. This series is essentially similar at all the points at which a complete section is to be seen. At the summit of Whittenberg Hill a series of the Miocene sediments, some hundreds of feet in thickness, have conglomeratic beds at their base, with a thickness of eight or ten feet, containing pebbles of granite and crystalline limestone.

On Tomales Point, opposite the Skinner Ranch, a similar series overlies the granites. The conglomerates at this point are not more than two or three feet in thickness. By far the most important occurrence of basal conglomerate is at the southwestern extremity of the peninsula, and especially in the immediate vicinity of the Point Reyes Lighthouse. The axis and southern face of the ridge extending east and west, is of granite. This is overlain along the northern slope by heavy beds of conglomerate, dipping steeply north-

ward. At the western end of the ridge, below the light-keepers' dwellings, and along the shore both at the south and west for a short distance, the conglomerates have a thickness of at least three hundred feet. The dip here is generally about 35° toward the west, though some of it is steeper.

The conglomerates here are not of uniform composition, but are made up of large boulders, cobblestones, pebbles, and sand that are very irregularly distributed. The basal portion of the series is somewhat distinct from these conglomerates, although it is apparently conformable with them. It consists of a dark sandy shale, about fifty or sixty feet in thickness, that holds its position pretty constantly throughout the whole length of the ridge. It contains a few layers of a calcareous concretionary material, in which search was made for fossils, though without success. This shale rests directly upon the granite, and is overlain above by massive beds of conglomerate. It seemed a little surprising that it should be found in this position, and at first suggested an earlier age, but its regularity and comformability below the conglomerates indicate that it marks only a change of conditions while yet below water level. The conglomerates are evidently shore deposits, while the shales are probably not.

The heaviest boulders that were seen in these conglomerates are in their upper portions near the lighthouse, where some of them measure four or five feet in length. There is no ready explanation of this fact, unless we suppose that the changes connected with the formation of these conglomerates were progressive, and in their later stages moved the shore-line only a little farther seaward, thus depositing heavier material upon that which had previously been formed farther from shore. Along the shore of Drake's Bay, where the granite crops out on the beach, the conglomerates are less than one hundred feet in thickness, and rest directly upon the granite, without the occurrence of the shales that intervene at other points along the ridge. The stones and pebbles of these conglomerates are mainly of granite and quartzite, with an occasional representative of a hard, dark, porphyritic rock and a little slate.

Succeeding the conglomerates at all the localities mentioned, are thick beds of sandstone of a light yellowish color. They are

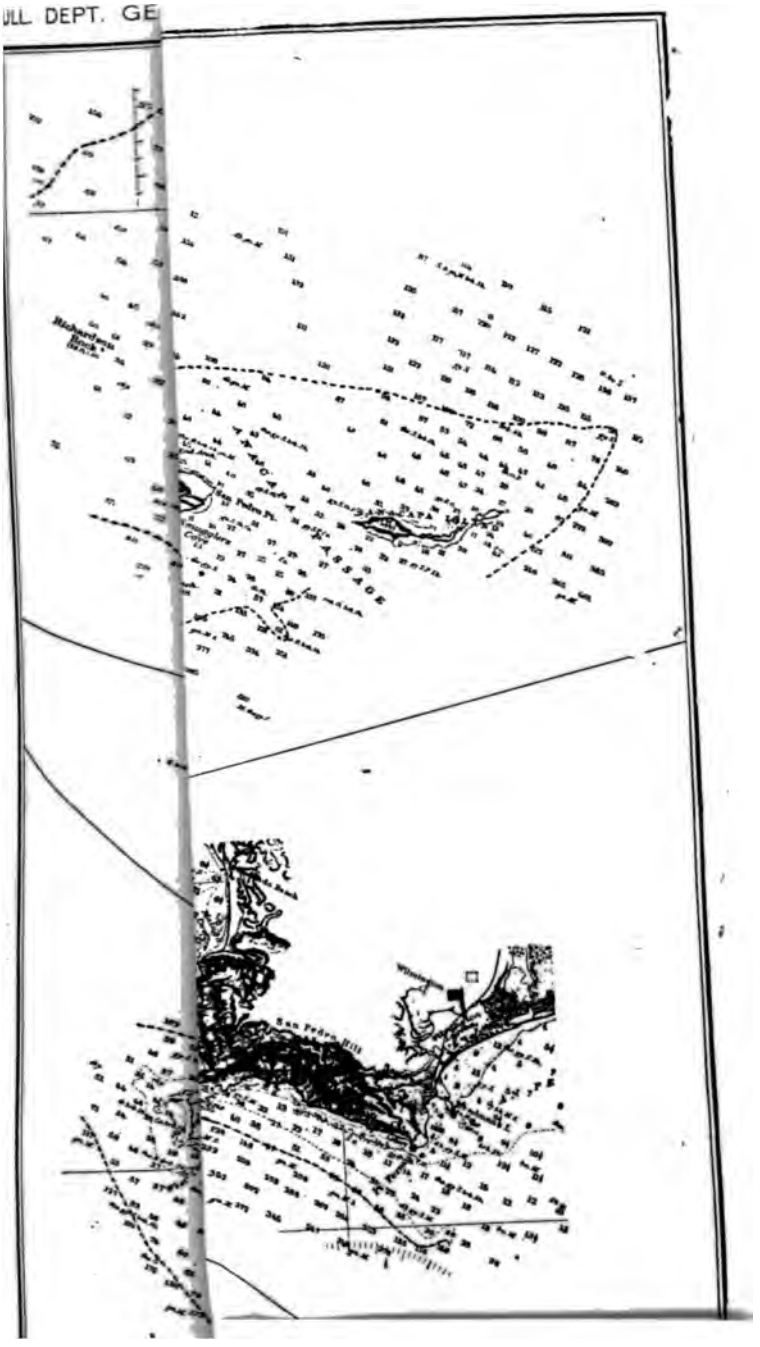
moderately coarse-grained and soft, yielding readily to the action of the weather, and are often excavated by the wind into small caves and hollows.

On Tomales Point a light yellow sandstone overlies the granite along its eastern border, and in places extends to the water's edge, along the shore of the bay. At the beach, west of Skinner's Ranch, an excellent section of the rocks is exposed in the cliffs. Resting upon the granite is a series of sedimentary rocks consisting of (1) a few feet of coarse conglomerate; (2) a yellowish sandstone, more or less massive, about one hundred feet in thickness; (3) sixty feet or more of whitish, thin-bedded shale. The series is entirely conformable, and doubtless all belongs to the same period of sedimentation.

The sandstones of the peninsula have apparently been derived largely from the granite and consist of coarse quartz sand, scales of mica, and kaolin-like material, all of which diminish gradually as one ascends the series. The dip of the series varies with its location. On Tomales Point it is about 20° toward the southeast, and away from the cliffs facing the ocean. There can be little doubt that here as well as at the lighthouse ridge a large body of granite has been worn away by the action of the waves. The granitic rocks, lying off shore at both places, give evidence of the same thing.

Figure 1.—Section drawn northeast and southwest through Whittenberg Hill.

Along the summit of the ridge, west of Point Reyes Station, there are sandstones, similar in character to those already described, overlying the granites and metamorphic limestone. It has here a thickness of about one hundred and fifty feet, which has been well exposed by faulting. The sandstones dip steeply to the west and are overlain in places by remnants of thin-bedded shale, and they probably also extend beneath the white shale that makes up the body of the lower hills lying toward the west. Along the western slopes of Vision Hill and in Bear Valley a similar sandstone occurs in the same relation to the granite and white shale. Along the western shore of Drake's Bay are sandstones of a loose, crumbling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ANACAPA PASSAGE
San Pedro Hills

nature, forming the cliffs that are so conspicuous from the mouth of Bear Valley. They are of a light yellow color and are thin-bedded, dipping gently away from the granites and overlying the conglomerates along the northern slope of the ridge. To the northward they pass by insensible gradations into whiter and more shaly material as they ascend the series.

On the peninsula the shales cover the larger part of its area, underlying the lower portions surrounding Drake's Bay and Estero, and composing the lower hills west of the main granitic ridge. In the lower portion of the peninsula they dip at a low angle and are very little disturbed, but along their western margin their inclination is very much greater. They have here been faulted and thrown into a series of short monoclines in which the dip sometimes amounts to as much as 45°.

At the summit of Whittenberg Hill the shales have a somewhat darker color than ordinarily, though in other respects they retain their characteristic features. The minute casts of foraminifera are abundant in them and they are composed of essentially the same material as the whiter beds are elsewhere. On account of the peculiarities of their stratification the section at the summit of this hill deserves more than a passing notice. It consists mostly of the finer-grained material composing the main body of the formation, in which are interstratified several layers of a coarse sandy character. These sandy layers, which are usually less than a foot in thickness, form a striking contrast to the strata of finer grain in which they are intercalated. An explanation of this peculiar phenomenon is not very easily made. Possibly they have only a limited extent and are records rather of fluctuating currents than of any considerable disturbances.

Figure 2.—Section drawn east and west just south of White Gulch.

It is seen from the above description that the Miocene sediments, lying between the main granite ridge and smaller area at the southwestern angle of the peninsula, have been gently folded into a broad

syncline, the middle of which is marked by the depression about Drake's Estero. Along the margins of the syncline the rocks dip steeply, while at its center they are more nearly horizontal. The general axial direction of the fold lies nearly parallel to shore, extending toward the Golden Gate. The development of the fold is doubtless connected with the movements of the block that are discussed in a later section.

Petrographic Character.—The petrographic character of the shales which form the principal member of the Miocene series has already been the subject of considerable study at other points of the coast.[1] Nothing of great importance has been discovered on the peninsula, not already known from other regions, and their petrography would be merely a repetition of what has been said before. In texture they vary from a tolerably granular, sandy phase to what might be called flinty. In Bear Valley and west of Whittenberg Hill the compact, somewhat vitreous and banded phase is more frequent, though this appears to be an areal rather than a stratigraphical variation. Such portions of the shale are both less porous and less bituminous than the more granular portions. West of Drake's Estero the shales are sandy and the amount of bituminous matter is very much greater than in the more compact portions. This is commonly seen in the fetid character of the water rising from them.

Origin of the Shales.—The origin of these shales is of an especial interest, since while they are seemingly unique in character there are certain homologies between them and other formations with which they have historically no connection. In thin sections and in fresh hand specimens may frequently be seen, even in the porcelanous varieties, small lath-shaped crystals resembling feldspar. The ashy or pumice-like character of much of the series at Monterey and Carmelo Bays led Professor Lawson to suggest that possibly volcanic eruptions had been the source of most of the material that composes these shales. The hypothesis finds some support in the chemical composition of the shales, which resembles

[1] Bull. Dept. Geol. Univ. Cal., Vol. 1, pp. 1–59; Vol. 2, pp. 1–92; Proc. Cal. Acad. Sci., Vol. 1, No. 1, 3d Series.

that of an acid rhyolite. This hypothesis, however, could hardly account for the whole of the vast accumulations of sediments that appear to be physically so similar throughout the Coast Ranges, for while there are acid rhyolites found in these ranges, no source has yet been discovered adequate to furnish so large a body of material.

On the other hand, it has been urged by Fairbanks[1] and conclusively shown by W. S. T. Smith[2] that at least a large portion of the series is of organic origin. The evidences of this derivation are mainly three: (1) The shales are everywhere more or less bituminous. No other source of the bituminous matter is more probable than that of organic remains. Yet fossil shells and bones have not been found in great abundance in them, and therefore the bitumen must have been derived from organisms, the hard parts of which have largely disappeared. (2) Scattered tests and fragments of Diatomaceæ and other siliceous organisms have been found in many of the beds, generally in an imperfect state of preservation. These have been most satisfactorily found at Monterey and on the island of Santa Catalina. (3) The colloid nature of the silica, which often forms as much as 90 per cent of the rock, is such as is commonly the result of organic secretion. Samples of the shale tested by W. S. T. Smith, lost by a treatment with potassium hydrate over 70 per cent of their weight. Fairbanks states that in a sample treated by him with the same solvent the loss was as great as 89 per cent of the original powder, which must therefore have been almost the whole of the silica. A sample from the peninsula of Point Reyes obtained from the beach south of White Gulch was subjected to a similar treatment, with the result that all but 26.75 per cent of the powder was dissolved. These tests clearly show the opaline nature of the silica which in these shales usually is either amorphous or has an organic structure.

In support of the volcanic origin of a very large part of the series, however, each of the above authors has contributed reliable evidence. On the island of Santa Catalina volcanic tuff is associated with the Miocene shale.

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[1] Bull. Dept. Geol. Univ. Cal., Vol. 2, pp. 9–14.

[2] Proc. Cal. Acad. Sci., 3d series, Vol. 1, No. 1, pp. 43–49.

In the vicinity of San Luis Obispo,[1] according to Fairbanks, the Miocene series has a thickness of 6,000 to 8,000 feet, in which occur beds of volcanic ash several hundred feet in thickness. Thinner beds of the same material were found in the lower portion of the Miocene series of Point Sal.[2] It appears, therefore, to have been satisfactorily shown that the material composing these deposits has been derived in part from both these sources.

One of the difficulties met with in the study of the bituminous shales of this series, has been to account for the absence of siliceous organic structures, and the presence of the silica in an amorphous or pulverent condition.

Why should there not be a greater abundance of the casts of diatomaceæ, radiolaria, or sponge spicules, if these have been the chief contributors to the silica of the deposits?

But whatever its source, it is evident, as Professor Lawson has shown, that the silica has undergone a secondary solution and redisposition as a pulverulent or gelatinous silica. This action has been attributed to sea water by both Lawson and Fairbanks.

Another agent of solution, however, has been shown to be both more efficient for this purpose and more closely connected with the mass of accumulating organic remains even than the sea water itself. That is the humus acids resulting from the slow decomposition of the soft organic tissues.

In a paper by Alexis A. Julien[3] it is shown that not only is this a possible explanation of the segregation or concentration of silica into the flinty layers and nodules of chalk, but it is even probably the correct interpretation to be attached to many of the masses of bedded cherts and jaspers in both Mesozoic and Paleozoic rocks. In this connection the author says:—

"The established solubility of silica in solutions of the azohumic acids therefore, suggests that, during the consolidation of the deep-sea sediment, such a solution of disseminated silica by albuminoids and by acids of this character is constantly in progress, etc."

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[1] Jour. Geol. 1898, Vol. 6, No. 6, p. 562.

[2] Bull. Dept. Geol. Univ. Cal., Vol. 2, p. 16.

[3] Proc. Am. Ass. Adv. Sci., Vol. 28, pp. 311–410.

A similar explanation has been offered for the well-known fact of the silicification of fossils, that is, for their replacement by silica. Professor LeConte has suggested a similar explanation for the silicification of wood.[1]

The probable agency of an organic solvent for the silica of the bituminous shales was suspected from an interesting occurrence on the peninsula. The remains of a cetacean were discovered buried in the bituminous shales of Drake's Bay. They were encased in an oblong oval crust of compact siliceous matter, which had the general appearance of a siliceous nodule of large dimensions. From one end of this concretion (?) the bones protruded, and even these were crusted over with a bead-like layer of opaline silica. There lacks, therefore, no link in the chain of evidence that points to the organic derivation of a large part, if not even the larger part, of the white shales of the Coast Range Miocene. Yet the volcanic source of some of the strata is no less satisfactorily shown.

Terrace Formations.—The Pleistocene deposits, only a part of which are represented upon the map, are usually coarse arkose detritus with an indistinct horizontal stratification. They are found, generally, in the larger depressions of the peninsula, and range in elevation from 500 feet downward. They form a series of low, broad hills, extending along the middle of the valley near Olema, and occur at intervals upon both shores of Tomales Bay, forming there a system of low bench-like terraces below 200 feet in height. West of the main ridge they are found in occasional patches around the flanks of the hills at the head of Drake's Estero, and north of Abbott's Lagoon. Along the county road, crossing the hills, they have an elevation of about 500 feet, and consist of granitic gravels and pebbles of white shales. No fossils have yet been found in them. A beautiful section of these deposits is to be seen in the cliffs east of Drake's Bay, where 50 or 60 feet of gravels are found capping the Miocene shales.

Recent Sands.—Along the western margin of the peninsula there are deposits of irregularly stratified or unstratified sand which has

[1] Am. Jour. Sci., Vol. 19, p. 181.—Elem. Geol., p. 193.

been carried up, and to some extent, sorted by the winds. Along the greater portion of the coast, which is low and rolling, these sands are the ordinary beach sands extending inland for a mile or more, but at two or three points they have a different character, and a considerably greater thickness.

At the Pierce Ranch, and still farther north on Tomales Point, there are deposits of fine sand having a brownish color and a much firmer bedding than ordinary beach sand. The short, deep ravines cutting down through them show depths of more than one hundred feet, and appear not to have reached bed-rock at that depth. They contain veins and streaks of iron oxide that have been segregated by the action of the surface water, and these veins stand out in relief upon the faces of the steep sides of the ravines. The elevation of the surface of these sand deposits above sea level is about 300 feet at their highest point. At the northern end of the ocean beach, near the lighthouse enclosures, there are similar deposits of about the same depth and elevation. They consist of the finer and lighter material of the beach wash, which has been carried up by the winds to higher levels.

Overwash Gravels.—Deposits resulting from recent atmospheric erosion are not uncommon, and may sometimes be mistaken for the terrace gravels already described. They occur along the lower slopes of the hills and cap some of the sea-cliffs to the east of Drake's Bay. They have not the regular stratification, though, of marine deposits, and so far as observed have no considerable thickness.

Geology of the Farallone Islands.—According to Mr. J. W. Blankinship,[1] formerly a student of the University of California, who visited those islands with Charles A. Keeler, the geology of the Farallones is quite similar to that of the promontory of Point Reyes, being that of a basement of granitic rocks overlain by massive beds of heavy conglomerate. The conglomerate is found along the northern and western sides of the group and was thought to dip northward. Distinct terraces were found surrounding the larger island, but at a lower level than any that were observed

[1] Zoe, Vol. 3, 1892, p. 145.

at Point Reyes. The terrace is best developed on the southeastern margin, or perhaps it may be here only better preserved.

STRUCTURE.

Crust Block.—The peninsula of Point Reyes, including the hilly coastal border south of Bear Valley reaching to Baulinas Bay, constitutes an orographic block that has in its oscillations during later geological periods been largely independent of the adjacent mainland. The eastern boundary of this block is the Baulinas-Tomales depression, which reaches the ocean in the two opposite directions. The submarine limits are not so apparent, though there is no reason for believing that they lie within that of the great sub-oceanic declivity situated but a few miles westward. How far the block may extend to the north and south may be inferred from facts only briefly considered here, yet such that leave the question not altogether conjectural. The surface of the block is a shallow basin or trough in which rest the Miocene and later sediments occupying the central portion of the peninsula. Evidently the Farallones form one of the outposts of this orographic block and have participated in all of its principal disturbances, which have probably been in accord with those of the Montara block lying south of the Golden Gate.

Faults.—The evidences of faulting along the Baulinas-Tomales Valley are to be seen both in the topography and in the general stratigraphic and petrographic relations. East of the valley the long gentle slopes and low rolling ridges of the Franciscan series indicate an old topography, yet the transition to the narrow valley-bottom is abrupt. The western border of the valley is formed by the high, steep ridge of granitic rocks. This ridge is in most places capped by Miocene strata dipping to the westward away from the valley. So far as observed, these Miocene sediments are not to be found eastward of the valley. Either they have never been deposited there, or, as is more probable, they have been so long above water and subject to aerial erosion that they have been all removed. South of Bear Valley, where the rocks of the Franciscan series are more common, there may be still other

evidence. There is also some evidence in the almost rectilinear character and direction of the depression itself.

Professor Lawson has described[1] a system of faulting on the San Francisco peninsula, separating the blocks of San Bruno and Montara Mountains, the main line of which presents a throw of 7,000 feet, according to estimates made by him. The strike of this fault-line carries it out into the ocean to the west of the Golden Gate. Looking at any good map of the region it is at once apparent that the projection of this fault-line and the Baulinas-Tomales depression almostly exactly coincide. It seems more than probable that the valley and escarpment of Point Reyes peninsula marks the continuation of the faulting which is so pronounced at San Bruno Mountain.

Only rough estimates can be made at present as to the amount of faulting that has taken place along this valley. We have supposed the thickness of Miocene sediments on the peninsula to be not less than 500 feet. The lowest member of the series, coarse gray sandstone, is found capping the granite ridge at an elevation of over 1,200 feet. If the whole of the series were supposed to have been superimposed upon this, with perhaps more that at the present does not exist, and the entire body of this complex series to have been lifted from the level of a few hundred feet below the ocean surface to its present elevation, the amount of the uplift can not have been less than 2,000 feet.

Considerable subsidiary faulting has taken place along the escarpment west of the valley. To the west and southwest of Point Reyes Station the system of faulting has been very complex, especially in the vicinity of the small area of "crushed granite" that has been previously described. It is not impossible that Bear Valley owes its origin to some of the minor faults cutting transversely across the ridge. This, however, remains to be proved.

The major fault-plane along which the displacement has mainly taken place perhaps lies nearest the western margin of the valley; or, rather, the western margin presents something of the

[1] 15th An. Rept. U. S. Geol. Sur., p. 468, etc.

granitic surface along which the faulting has progressed. The general appearance is that of a normal fault, and there is some specific evidence pointing in this direction. The withdrawal of the Franciscan terrane lying to the east has left detachments of those rocks in somewhat elevated positions upon the flanks of the granite. Similar remnants of Miocene rocks along the western side of the valley opposite Olema also present evidence to the same effect, yet the long succession of oscillatory movements that have affected this region, and of which the present displacements are a partial result, makes it difficult to make accurate statements except of the most general kind. The faulting is evidently complicated as one would expect as a result of complicated movements. If there is supposed a downward enlargement of the granitic batholite, then clearly normal faulting has been the most pronounced, as is shown by the rocks lying along the flanks of the granite.

The small body of foraminiferal limestone upon the eastern slope of Whittenberg Hill is thought to belong to a low horizon of the Franciscan series, wholly concealed by depression upon the eastern margin of the valley. That there has been, on the other hand, enormous lateral pressure at times, and perhaps accompanying some of the oscillations, seems evident from the general sheared and broken character of the granite in all parts of the peninsula. This is particularly apparent in the zone of crushed granite lying west of Olema. Lateral compression also seems to offer the best explanation of the synclinal deformation of the Miocene series in the central part of the peninsula between the areas of granite. But if the downward peripheral enlargement of the granite in subterranean levels be supposed, lateral compression could not result in normal faulting, but would produce an overthrust and a consequent depression of the granitic block instead of an elevation. And if the time element in the complexity be considered it may well be supposed that this has been among the phenomena that have taken place. It might, therefore, seem that the successive elevations and depressions of the orographic block, that are to be hereafter described, have had their causes partially in successive compressions and stretchings of the coastal crust.

GEOMORPHY.

The present relief of the peninsula is not complex and may best be described under the following headings, each of which represents a distinct stage in its historical development, though not all of the stages are included.

Main Ridges.—The greatest elevations are found in the principal ridge following the western shore of Tomales Bay, two points of which attain a height of about 1,300 feet. Between and on either side of these the altitude of the ridge declines. Whittenberg Hill stands about two miles southwest of Point Reyes Station.

B Figure 3.—Whittenberg Hill, looking south; Olema on the left, ocean on the right. A

It consists mainly of granite mantled over from the west by a tolerably thick monocline of Miocene sediments. Its northern and western slopes are accordingly much more gentle than its southern and eastern, which are rather abrupt. Five miles to the northwest and nearly opposite the head of Drake's Estero is a more broadly rounded granitic dome somewhat higher than Whittenberg, known as Vision Hill. Its summit is oblong, consisting of a few minor

A Figure 4.—Profile of Vision Hill, looking north; ocean on the left, Tomales Bay on the right. C

rocky points resting upon a rounded mesa-like platform from which extend a number of bold radial ridges. The summit of this platform probably represents a miniature peneplain. The ridge between these two elevations is a succession of lower summits mainly or entirely made up of granite rocks. North of Vision Hill the ridge is similarly a succession of hills gradually declining in elevation in the direction of Tomales Head.

The second ridge that deserves notice is one made conspicuous by its isolation rather than by its elevation. It is at the southwest angle of the field. Its greatest height is about 600 feet, and embraces a limb of the syncline of Miocene strata resting upon the granitic axis. The cliffs facing the south are almost entirely of granite, above which the sedimentary beds rise in a few prominent points. The general level of this ridge is about that of the next topographic feature to be described, though it can hardly be classed together with it.

Terraces.—Remnants of two terraces are more or less clearly visible, chiefly west of the principal granite ridge. The higher of these terraces which is much less perfectly preserved than the other is to be traced mainly in a system of rounded hill-tops the general elevation of which is about 600 or 700 feet. They are most satisfactorily seen from the north or south, and are in two groups, the larger of which is immediately east of Drake's Bay, the other farther to the north. The form of these hills is one that is peculiar to the much-faulted and differently-weathering Miocene sediments of the coastal border. The summits are broadly rounded, the lower slopes are steep, and the hills are separated by long V-shaped cañons.

The lower terrace is much more striking in its uniformity and extent. It is one of the clear records of a disturbance very widely felt along the coast north and south. Its general level is about 200 feet or a little more, though its central portion is somewhat lower. This terrace is almost continuous with that of Duxbury Point, and is the one mentioned by Professor Lawson[1] as the wave-cut terrace of Point Reyes. It is deeply incised both by narrow cañons descending from the higher ridges, and by the long finger-like extensions of Drake's Estero, forming a system of lagoons. The central portion of this terrace, in the immediate vicinity of this estero, seems to have suffered a local sagging which has left the land to the westward at a much lower lever than that of the terrace proper.

Shore-lines.—With the exception of the long sandy beach on

[1] Bull. Dept. Geol. Univ. Cal., Vol. 1, p. 245.

the western side of the peninsula all the shores are steep or precipitous. The cliffs bordering Drake's Bay have a nearly uniform height of 200 feet. On both sides of the northern promontory the cliffs range from 200 to 400 feet in height, and this continues along a large part of the western shore of Tomales Bay.

Submarine Topography.—Although there is nothing particularly instructive in the submarine topography immediately bordering the peninsula, yet this body being but a part of a crustal block that is quite extensive it is not amiss to go a little beyond its boundaries for information regarding its orographic history. The maps of the Coast and Geodetic Survey furnish valuable data for studying these problems. Westward from the peninsular border the bottom of the sea slopes rather steeply for a mile or more until a depth of nearly 200 feet is reached, beyond which line the inclination is less than twenty feet per mile to the edge of the great submarine bench, some twenty miles off shore, where the floor plunges suddenly downward. Toward the south, between the Farallone Islands and the mainland, the submarine terrace is still better developed.

Its average depth is about 200 feet. Although this portion of the submarine terrace is opposite the Golden Gate, from which issue the waters of the bay of San Francisco with all its drainage, there is but little in its topography to indicate a great accumulation of sediments from that source. When compared to the adjoining portions of the terrace north and south, it is approximately a perfect continuation of the same level. A depression or channel extends inwardly between the Farallones and Point Reyes peninsula which possibly marks a former channel of the emboguing river. Essentially this channel accords with the interpretation of this submarine shelf, which regards it as an earlier terrace formed when the land stood at a higher level.

Drainage.—The drainage of the peninsula is in two opposite directions and the features of its topography accord with those of the general topographic development. The courses of all the streams may readily be divided into three portions. There are the ordinary steeper cañons at the head, the stretch of narrow gorge with a gentler slope, and lastly a usual stretch of a level

semimarsh portion through which the current is ordinarily sluggish. The drainage of the eastern margin is directly into Tomales Bay by short and tolerably rapid streams. That of the western portion is by longer streams, most of which find their way into Drake's Bay either directly or indirectly. Many of them converge into Drake's Estero, the outline of which beautifully illustrates the effect of a drowned valley.

DYNAMIC HISTORY.

Granitic Intrusion.—Evidences of the earlier disturbances of the coast, either epeirogenic or orogenic, are not well shown upon the peninsula. The earliest of which there is any clear record to be found is that of the granitic intrusion into the older crust of sedimentary rocks which has resulted in the distortion and metamorphism of the latter. There is no evidence yet recognized that fixes with any certainty the date of this event. In the absence, therefore, of contradictory facts it may be supposed to be contemporaneous with some of the granites of the Sierra Nevada. At the same time the relatively slight metamorphism of much of the Franciscan (Golden Gate) series, even in actual contact with the granites, makes it evident that the intusion took place prior to the deposition of these rocks, which mark the next epoch of which there is any record here.

Subsequent Movements.—After the erosion, which followed the granitic up-thrust, there was a prolonged period of subsidence, during which the strata of the Franciscan rocks were laid down. This event is recorded not only by the small body of limestone and slate found west of Olema, but also by the whole Franciscan terrane lying to the eastward of the peninsula.

From our knowledge of oscillations that have affected other and neighboring portions of the coast, it would seem that there must have been movements here during the Cretaceous and early Tertiary which have not left legible records.

From the beginning of the Miocene, however, our knowledge is more perfect. The character and order of the Miocene deposits show that at the beginning and throughout the Miocene the movement of the land was downward.

The regular and normal succession of these strata indicate a gradual subsidence and retreat of the shore line, which probably extended considerably eastward of the Olema Valley, as shown by the character of the later Miocene sediments, which could hardly have been deposited near shore, and by the fact also that farther eastward the Miocene is known to occur upon the mainland. Following the Miocene depression was an uplift and period of erosion, during which the strata just deposited were subjected to erosion, the extent of which cannot here be seen. There are reasons, however, for believing it was considerable. Perhaps, also, a portion of the folding of the series took place with this uplift, though it may have been subsequently very much increased.

As to the faulting that forms so conspicuous a feature of the topography, it is not known to have had even its inception prior to the close of this post-Miocene land period, but apparently it was connected with the next succeeding movements of the land, the records of which are best known outside of this field. The Pliocene of the Coast Ranges is known to contain at least two series of deposits, the San Pablo[1] and the Merced,[2] which are unconformably related to each other. Both appear to be represented in the near vicinity, though neither of them within the boundaries of the peninsula. Near the town of Tomales are beds supposed to be of San Pablo age, while near Baulinas are others that are probably to be classed with the Merced. If these suppositions are correct, the development of the fault seems to have been progressive from the beginning of the Pliocene. The San Pablo formation is not known to the west of this fault-line, either here or elsewhere, while the Merced seems to be confined in its distribution to the immediate vicinity of the coast. The evidence afforded by this peculiar circumstance seems to indicate that the oscillations of the two contiguous blocks have been independent throughout the Pliocene, and that the faulting began with a subsidence which covered at least a large portion of the mainland with San Pablo marine deposits.

The re-elevation of this block was perhaps accompanied by a

[1] Bull. Dept. Geol. Univ. Cal., Vol. 2, No. 4; Jour. Geol., Vol. 6, No. 6.
[2] 15th An. Rept. U. S. Geol. Sur., pp. 409-476.

downward movement of the other, which resulted in an accumulation of the Merced deposits of considerable thickness, in its typical locality south of the Golden Gate.

Following the Merced subsidence, there was probably a widespread orogenic movement, which quite singularly seems to have disturbed and tilted the lately-formed Pliocene strata, without greatly increasing their elevation. The nature of these movements is not very clear, but evidently the land both east and west, that is to say, both orographic blocks, were simultaneously left at a level, considerably below the present one, from which they slowly emerged, forming the terraces previously described, and the corresponding deposits of Pleistocene gravels, which have been called by Professor Lawson the "terrace formations." These deposits, however, appear to have been formed only during the earlier stages of the uplift, or rather only the earlier deposits are at present observable, the latter being now submerged by a subsequent inundation.

The Miocene beds of the peninsula have been deeply scarred by the long-continued atmospheric action, probably in part effected during the period of terracing and elevation, but mainly as it seems at a prior epoch, since the detritus of the terraces is mostly confined to the valleys previously excavated. Three quite distinct terraces are recognizable, marking the principal pauses in the process of this elevation. These have already been described, two of which are to be seen along the hills, while the third is entirely submarine. It appears, therefore, that the gradual rise of land which is marked by these benches continued until the shore-line was thrown westward, nearly to the verge of the continental bench, at which time the land must have stood at a level of more than 200 feet above its present position. This is shown by the broad submarine terraces just alluded to. From this altitude there has been a sinking, more or less general, which is probably yet in action.

This subsidence has resulted in two well-marked effects: (1) The beveling of the submarine terrace, which is in part, at least, due to such causes; and (2) the inundation of the stream valleys, which is illustrated in Drake's Estero.

SUMMARY AND CONCLUSION.

The additions made to our former knowledge of west coast geology by the present study are not great. Aside from the contribution to areal geology they are mainly of the nature of suggestions. An effort has been made to confirm as far as possible by facts gathered in this field, what appear to be correct conclusions reached by studies of other portions of the coast. Diverse conclusions have been reached concerning certain problems here met with, and in so far as the facts observed in this field bear upon them they have been given their due weight.

Granite.—The petrographical characters of the granite of the peninsula harmonize essentially with most that is met with in the Coast Ranges southward and with them it forms a more or less satisfactory unit. It differs from the rocks of the Sierra Nevada that have been termed granodiorite both mineralogically and, as far as can be told, chemically. It has its nearest allies in granites of the Klamath Mountains which have not yet been formally described. The age is uncertain but it is, perhaps, contemporaneous with some of the granites, both in the Sierra Nevada and in the Klamath Mountains. If so, it is probably of an age younger than the Mariposa Beds of the Jurassic and earlier than the deposition of the Franciscan (Golden Gate) series.

Ancient Crust.—The rocks of the pre-granite crust so far as they can be found form a series of limestone, quartzite and a highly metamorphosed crystalline schist. Their physical and petrographical constants, as far as they can be learned, ally these rocks to the Paleozoic, and there is an analogy between them and certain phases of the Devonian rocks of northern California.

Miocene.—Of the later formations only the Miocene has furnished evidence of any important bearing upon lithology. Certain occurrences upon the peninsula are interpreted to confirm the organic origin of the bituminous shales, as was suggested by earlier writers and more recently advocated by Fairbanks. The highly siliceous character of the shales is thus accounted for while at the same time the structureless and amorphous condition of the silica described by both Lawson and Fairbanks is readily

explained as a reactionary result of humous acids that are known to originate in the decomposition of organic tissues. The effects of these acids upon organic silica have been the subject of a study by Julien to which reference is made. The volcanic origin of much of the total volume of rocks in this series (Monterey) is also fully recognized for other portions of the coast.

The Miocene sediments lie in a broad syncline resting at both margins upon the granite. Its folding has been affected by movements of the orographic block during post-Miocene times which at the same time resulted in a great amount of faulting and the vertical displacement of one of the contiguous blocks to the extent of at least 2,000 feet and perhaps more.

Pleistocene deposits are strewn over the peninsula and rest generally in an undisturbed position upon all parts, making it apparent that the last great movements of the region have affected equally both orographic blocks here referred to, showing plainly that the faulting antedates entirely the Pleistocene Terrace Formations and that it was probably progressive in its development from the opening of the San Pablo epoch, beginning with the subsidence of that time.

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SOME ASPECTS OF EROSION

IN

RELATION TO THE THEORY OF THE PENEPLAIN.*

BY

W. S. TANGIER SMITH.

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INTRODUCTION.

A RECENT article by Prof. R. S. Tarr† has raised a question as to the validity of the theory of peneplains, and at the same time proposed a different explanation for the same phenomena, under the

*Since this paper was written, an article has been published by Prof. N. S. Shaler (Bulletin of the Geological Society of America, Vol. 10, pp. 263-276, "Spacing of Rivers with Reference to Hypothesis of Base-leveling"), in which he reaches conclusions similar to some of those presented here, though by a different line of reasoning.

† The Peneplain, Am. Geol., Vol. XXI, June, 1898, pp. 351-370.

term *beveling*. A later article by Prof. W. M. Davis,* in reply to Professor Tarr, fails (partly through misinterpretation) to meet fully his objections to the established theory, or to overthrow his arguments for a new one, and the outcome of the discussion leaves it clear that we should not continue to hold to the peneplain idea without a further sifting of the evidence both for and against it.

It remains, therefore, to be determined how far the accepted theory of peneplains may still be applied, and how far the phenomena usually classed under that head may or should be accounted for by laws of erosion working under ordinary conditions. To offer some suggestions on these two points is the object of the present paper.

DEFINITION OF THE TERM PENEPLAIN.

It is well, first of all, to review the definition of this term, since it has been used loosely by some writers. Davis† has defined it as "a nearly featureless plain" produced by subaerial denudation. The use of the term is thus strictly limited to those topographic forms, whether of local or greater extent, which are produced by subaerial erosion alone, excluding all other forms of erosion, and all topographic forms due to deposition alone. It is apparent, from further discussion of the term, that the essential point of the definition is the wearing down of the land to an attitude *approaching base-level*—and therefore no plains, however formed, which do not fulfil this condition, can be called peneplains, even though otherwise similar in character. Finally, although the term does not include plains of submarine erosion or deposition, peneplains formed near the border of a continent would, of necessity, be associated with these other features to a greater or less extent.

The conception of peneplanation on which the following arguments are based may be stated thus: the reduction of a limited portion of land, by subaerial processes alone, to a condition of very moderate relief, near ultimate base-level. By "a limited portion of land" is meant here such an area as would form a natural geographical unit. This will usually be a mountain range, or other

* The Peneplain, Am. Geol., Vol. XXIII, April, 1899, pp. 207–239.

† Am. Journ. Sci., 1889, Ser. III, Vol. XXXVII, p. 430.

mountainous area. A series of ranges, in a given region, under similar conditions as regards general attitude, character of rocks, climate etc., would usually be worn down at the same rate, and might be considered as parts of a larger and complex geographical unit.

As illustrations of independent ranges, we may take the Sierra Nevadas and Coast Range of California. The latter might be reduced to a peneplain while the former was still far from that condition, since they are independent units, and the erosion of one range does not affect that of the other, except indirectly. It would be possible for both to be reduced to the peneplain condition at the same time, but this would not be on account of any causal connection between the two. If conditions favorable to peneplanation should obtain at the same time in both, the more rapid erosion in the higher range, and the progressive decrease in rate of erosion in the topographically older one, with advance in topographic age, might so far counterbalance the original differences between them that by the time the older range had reached the peneplain form, the other would be not far from the same condition. The probability of such a combination of circumstances is lessened, however, by the possibility of differential movements, and by actual differences in climate, character of the rocks and other conditions, in addition to the differences in average altitude and present degree of topographic development.

On the other hand, owing to similarity of conditions throughout the range (possible differential movements within the mass excepted), we should expect the whole of the Coast Range to be worn down as a unit. Although long before the general peneplain condition should be reached, partial or local peneplains might be developed along those parts of the stream courses nearest base-level, these could be of but very limited extent, until the range as a whole should begin to assume the same aspect.

OBJECTIONS TO THE THEORY OF PENEPLANATION.

Absence of Present Peneplains.—Professor Tarr's first important objection to the peneplain hypothesis is the fact that no such forms are found on the earth to-day, unchanged, as features of the present

topography.* His statements refer, without question, to recent, undissected peneplains, standing now at or near the level at which they were formed; and in this sense (which is quite different from the interpretation given to them by Professor Davis†) they form a valid argument against the unconditional acceptance of the peneplain explanation.

The absence of peneplains recently formed or in process of formation involves (as Professor Tarr points out and as Professor Davis admits) the assumption of different conditions in the past, when peneplains were formed, from those of the present, when peneplains do not form. If we assume that there have been in the past periods of relative quiescence, while the present is a time of comparatively greater movement, a minor difficulty still remains. Not only are there no present peneplains, unelevated and undissected, but those of the past, so far as known, are all elevated to a considerable height above sea-level. As it is beyond question that earth movements, at a given time, are not uniform over the earth's surface, nor even over continental areas, but, on the contrary, are very diverse in different regions, we should expect peneplains, which have been subjected to these movements in different parts of the world, to occupy, in consequence, more diverse positions than those in which they are found. That is, the many different oscillations would be likely to leave some peneplains at considerable elevations, to bury others, and to return others again to somewhere near their original position—near sea-level. If peneplains are so numerous as they are described, it seems strange that not a single example should appear anywhere near sea-level. This objection, however, may be disregarded if it can be shown (as the writer believes) that the occurrence of peneplains has been much less frequent than is commonly assumed.

Difficulty of Fulfilling Necessary Conditions.—Professor Tarr's next important argument is that the earth's crust would not remain stable long enough for the slow process of denudation to produce a peneplain.‡ It must be noted that while this statement includes

* Loc. cit., p. 353.

† Loc. cit., p. 227.

‡ Loc. cit., pp. 354 and 362.

two distinct ideas, (1) the instability of the earth's crust, and (2) the slowness of the process of denudation, these are considered only in their relation to each other. The objection can not, therefore, be answered by treating them separately, as Professor Davis has done.* It is not a question of the length of geologic time, nor of the stability of the earth's crust; the question is whether the crust would remain approximately quiet *long enough* for the completion of a certain very long process. For this reason we can not disregard the length of the process. The consideration of the rate of erosion, especially with advance in topographic age, is therefore a most important one.

Examples of the rate of erosion may be drawn from the mountain ranges of California. According to the observations of various writers† (and my own as well), erosion since the Glacial epoch, in the Sierra Nevadas, has been practically *nil*, but since the elevation of the range at the end of the Pliocene there has been sufficient time for the cutting of the deep gorges which incise the western slopes. The vertical range of cutting is great, reaching a maximum of several thousand feet, though the horizontal range is comparatively insignificant. The streams are young, and the total amount of material removed is small as compared with the bulk of the range. This cutting represents the results of the erosion of the whole post-Pliocene time—of which the post-Glacial, judging from this evidence, is such a small proportion.

Turning to the Coast Range, we have an approximate measure of the post-Pliocene erosion here in San Clemente Island,‡ the present stream cañons of which belong wholly to this period. In the main Coast Range the forms are mature, and quite unlike those of the Sierras or of San Clemente. The Coast Range forms appear to have been developed, in the main, during the post-Miocene elevation of the coast, and modified during the Pliocene depression. Judging, therefore, from these results, the post-Miocene interval of

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*Loc. cit., pp. 223–227.

†Tenth Ann. Rept., U. S. Geol. Survey, Pt. I., p. 28.
Seventeenth Ann. Rept., U. S. Geol. Survey, Pt. I., p. 710.
Geol. Atlas of U. S., Folio No. 39 (Truckee, Calif.), p. 6.

‡See Eighteenth Ann. Rept., U. S. Geol. Surv., Pt. I., p. 469, and Plate LXXXVII.

erosion was greatly longer than the post-Pliocene has been thus far. Differences in climate, altitude and other factors may have caused a more rapid erosion in the former, thus shortening somewhat the time which it is necessary to postulate; but even then the difference between the length of the post-Miocene interval and that of the post-Pliocene must remain very great.

The Coast Ranges are still far from the peneplain condition. What proportion of the original range has been already removed could not be estimated without knowing approximately the mass of the range at the beginning of post-Miocene times, beside taking account of the considerable amount removed during the Pliocene depression of the coast. That the total amount of erosion has been large can not be doubted; a guess might be hazarded at fifty per cent of the original mass of the range.

Even on the basis of such a rate of erosion as is thus shown, the formation of a peneplain could be brought within the range of possibility only by the assumption of the most favorable circumstances. That is, if it could be shown in any way that the Miocene time was as much longer than the post-Miocene as this appears to have been longer than the post-Pliocene, and if, as Dutton* has shown for the Colorado region, the climate of the Miocene was especially favorable to rapid erosion, it might be assumed that there would have been time for the formation of a peneplain during this epoch, provided that the land stood close to the same level during all that time. But if all these conditions were fulfilled, the difficulty still remains that the rate of erosion is not constant, but decreases progressively with advancing topographic age, and thus the time demanded for the reduction to a peneplain is much increased. Thus when we take into account not only the slowness of the process of erosion in general, but its increasing slowness with the wearing down of the land, the improbability that the earth's crust would remain sufficiently stable during such immense periods as would be required for the production of a peneplain under ordinary circumstances, becomes one of the most important objections to the hypothesis as an explanation of commonly existing forms.

* Monograph II., U. S. Geol. Surv., pp. 189–191.

LIMITATION OF THE TERM.

If the necessary conditions of peneplanation, then, are so difficult of fulfilment, it is certainly reasonable to suppose that actual and extensive peneplains could have been developed only in rare instances, where there was an unusual combination of the most favorable circumstances. But it is by no means necessary, on this account, to discard altogether the idea of the actual occurrence of peneplains.

It is possible that a given region may remain relatively quiet through a considerable geologic time. Such relative quiescence would allow of a continuous slow elevation, providing it was so slow that erosion could more than keep pace with it; or a slight depression, which, by decreasing the general elevation of the region, might shorten more or less the time required for peneplanation. The absence of given deposits from a region would mean, either that they were wholly removed after their deposition, or else that there never had been such deposits in that region. In the latter case there must have been either relative quiescence during the time in question, or else oscillations, in general above sea-level.

With variations in movement there have been also variations in other factors which affect the formation of peneplains, as rainfall, climate etc. Dutton * states that the climate of the Colorado region was much moister during the Miocene than at present, and that the excessive rainfall of that time aided in the immense erosion which took place in that region. Some regions may be more readily eroded, and thus more likely to be worn down to the condition of a peneplain than others, on account of differences in general characters of the rocks, in amount of elevation etc., as well as in climate and rainfall.

From the above it will be seen that the writer's own belief includes the theoretical possibility of peneplains and their probable actual occurrence, but only in rare instances, owing to the nature of the conditions under which they must be formed. If, then, actual peneplains are few, a large proportion of the features thus far described as such are probably due to some other cause. It

* Loc. cit.

should be noted here, however, that as a single peneplain may be, and, indeed, is likely to be, of great extent, its remnants in a more or less altered condition might give rise to descriptions of several peneplains, all of which were, in reality, parts of the same original form.

From the fact that all so-called peneplains found to-day (not buried) are elevated to a considerable altitude, none being found even approximating sea-level; and from the further fact that a more or less even sky-line is a feature found in the majority of upland regions which have been described of late years, we should be inclined to ascribe the "peneplained" or "beveled" character of such regions, as Professor Tarr has done, to some cause inherent in the processes of erosion under ordinary conditions, thus considering the even sky-line a characteristic of mountain ranges in general.

USE OF THE TERM BEVELING.

The term "beveling," as proposed by Professor Tarr,* has not been accurately defined, but it is apparently intended to cover all the phenomena of those features of the present topography to which the name of peneplains has been given, since the process is offered as a substitute for that of peneplanation. That is, a beveled surface is one in which there is an approximate uniformity of crests, combined with a slight slope or tilting of the whole. This is a direct application of the ordinary meaning of the word, since a beveled surface is defined as a plane surface which makes with another adjacent surface an angle which is not a right angle. Professor Davis' interpretation of the term as the mere "truncation" of individual peaks† seems, therefore, unnecessarily strained; and any criticism of the proposed explanation based on this conception of the meaning of the word, would fall to the ground, since truncation is not beveling.

According to Professor Tarr, an approximate uniformity of mountain crests is obtained through erosion, and this uniformity "would be greater near the sea, where development would have

* Loc. cit., p. 366.

† Loc. cit., p. 235.

been most advanced."* What the connection may be between the increase of uniformity near the sea and advance in development, is not made clear. By "near the sea" is evidently meant, in the lower stretches of the important stream courses; for where the main divides and stream courses are parallel to the coast-line, the statement as made would not necessarily hold. Apparently Professor Tarr's idea is that "beveling" begins at the lower end of the main stream courses, and since "in the coastal region there may well have been an approach to the condition of a local peneplain," † it would follow that the uniformity in this region would be most marked.

According to Professor Tarr's view, it is only the "peaks whose rocks were approximately the same in power of resistance" which "would in time approach each other in altitude," ‡ and the explanation will not account for the rough uniformity of many crests in mature regions where the rocks are quite different in power of resistance.

CONSIDERATIONS MODIFYING USE OF TERM.

It seems probable that Professor Tarr is correct in his main idea, that there is a certain beveling effect in the forces of erosion acting under ordinary conditions; and, further, that this will explain many cases of supposed peneplanation. But if it is true, the explanation given is inadequate to account for it, and some of the premises are wrongly assumed.

To state briefly the writer's view of the case: there is and should be, in all well-matured regions, a roughly even sky-line, or subequality in the altitudes of the ridges, due to subaerial denudation, as will be shown. (In a region which for any reason already presents in infancy an even sky-line, due, for instance, to peneplanation or marine abrasion, an approximate evenness of sky-line will probably be persistent from youth to old age.) In a region of mature drainage, neighboring streams of the same class, at corresponding points, will have their beds roughly at the same altitude,

* Loc. cit., p. 366.
† Loc. cit.
‡ Loc. cit., p. 368.

and the rate of cutting at these points will be approximately the same. If, then, as the writer believes, the altitude of a ridge depends for one of its chief factors on the altitude and rate of cutting in the adjacent stream bed; and if the altitude and rate of cutting in neighboring streams of the same class are approximately the same (as just stated), then the adjacent divides should approximate equal altitudes, other things being equal, and an evenness of sky-line in this region will result. These principles should apply to all parts of a drainage system alike, though for the purposes of the present discussion they will be referred to chiefly in connection with the main streams, as it is the uniformity of the main divides which gives a general effect of evenness of sky-line to the region.

In discussing the question of beveling, the "subequality of mountain heights" will be considered first, without taking into account the lack of horizontality ("tilting") which is associated with it. (This latter point will be taken up later.) Admitting the rough equality at the tree limit, let us consider the question of equality below that point, or the equality in those regions which may never have been above the tree line, bearing in mind that throughout the following discussion of drainage features, *mature topography is always postulated.*

Graded Slopes.—In a mature region the streams are in a graded condition. A graded stream is one whose "carrying power is reduced to" essential "equality with the load," and which is thus essentially in a "condition of balance between degrading and aggrading."* Along a stream course, unaffected by accidents from youth to old age, there should never be an absolute balance between degrading and aggrading. The stream *taken as a whole* is cutting all the time, until base-level is reached; but it cuts more slowly as its age increases. The rate of cutting is dependent on the length of the stream course and the elevation of its head-waters above its mouth (or the grade of the stream); and also on the amount of precipitation, general character of the rocks in which it cuts, and amount of material brought into the stream from the

*Wm. M. Davis: Physical Geography in the University; Journ. Geol., Vol. II., No. 1, Jan.-Feb., 1894, p 77.

adjacent slopes and tributary streams. On the other hand, the amount of material furnished by the slopes will be adjusted to the rate of cutting in the stream (as will be shown later), for the two are interdependent factors. After a stream has acquired a "tolerably systematic curve of descent," and its cutting has been adjusted to the factors given above, it would seem that it could be called a graded stream.

Thus the tendency of a stream is always to decrease its grade; and this may be done either by vertical corrasion, or by lateral corrasion, or by the two together. If a stream can not decrease its grade by vertical cutting it may do so by meandering, thus increasing the length of its course for a given fall.

If a stream empties into the ocean (as all streams do, either directly or indirectly, except such as empty into an inland basin without outlet) its vertical cutting is limited at its mouth. If, then, the stream preserves a systematic curve of descent, after it is once acquired, and is continually cutting except at sea-level, the amount of vertical corrasion must progressively decrease in going down stream, until it reaches zero at sea-level.

The slopes adjacent to a graded stream at any given point are slopes of equal erosion, for the erosion on such mature slopes must be everywhere essentially the same. If this were not the case, but if one part of the slope were more rapidly eroded than another, sooner or later the more rapid erosion would cause a decrease in the angle of the slope at this point, and in consequence of the decreased angle the rate of erosion would be, in turn, decreased, and would, therefore, in time become the same as that over the rest of the slope. Such adjusted slopes are graded slopes.

Erosion on all sides of a peak or on both sides of a divide, should be uniform; otherwise the summit of the peak or crest of the divide will shift until uniformity of erosion is attained. In homogeneous rocks, with equal precipitation at all points, the two slopes of a divide are of necessity equal. Hereafter the term *slope* will be used to refer to one slope of a divide or peak, from its base to, *and including*, its summit. The angle of a slope, even when fixed, is, of course, not the same from top to bottom.

The angle of the graded slope is dependent partly on the rate of erosion in the adjacent stream bed, and partly on the character

of the rock as regards its resistance to weathering. The angle varies further with lack of homogeneity in the rock, with variation in the structure and attitude of the rocks, and with differences in climate and in amount and kind of vegetation.

If the stream increases its rate of cutting, the part of the slope next the stream has its angle increased, and this increase of angle is gradually extended until the summit is reached, and the erosion over the entire surface of the slope is once more uniform and equivalent to that of the stream. If the rate of cutting of the stream is decreased, and consequently that at the base of the slope, the upper parts and summit, which are at first eroded more rapidly than the stream is cutting its channel, will soon be so reduced in their elevation above the stream, and the angle of slope, consequently, so decreased, that equilibrium will be restored.

A graded slope once established tends to maintain itself, and to be lowered only as the stream bed is lowered. If the stream is cutting rapidly, the summit is lowered rapidly; if the stream cuts slowly, the summit is lowered slowly, and the angle of the graded slope is less than in the former case. If the stream cuts at a uniform rate, the summit is lowered at the same rate, and the slope is maintained at a uniform angle. It would follow that in old age, when the streams cut very slowly, the angle of the graded slopes will be lower than in the earlier history, when the cutting was more rapid, and the summits, therefore, will not be so far above the stream beds.

Differential Erosion.—Since soft rocks are eroded more readily than hard ones, it would be necessary, in order that there should be equality of erosion, on a given slope, in hard and soft rocks, that the angle of slope be less in the soft rocks, and greater in the hard ones. It is generally assumed that differential erosion always takes place in areas containing both hard and soft rocks; but if graded slopes are free to develop, then the difference in rate of erosion between the hard and soft rocks will be compensated for, to a greater or less degree, by difference in the angles of the slopes. Such differences in slope, due to difference in resistance to erosion of the various rocks, may be observed almost anywhere in mountainous regions. An illustration is shown in Fig. 1, where the hills

vith gentler slopes, in the foreground, are of a readily weathered andstone, while near the center of the background may be seen a ill with steeper slopes, formed from more resistant cherts.

Figure 1.—View in the Coast Range of California, showing difference in slope due to difference in the character of the rocks.

On a single graded slope formed in rocks of varying degrees of esistance, or in a non-homogeneous rock, those parts formed in he most resistant rock will have the greatest angle, those formed n the least resistant, the least angle. Such a slope is a composite raded slope.

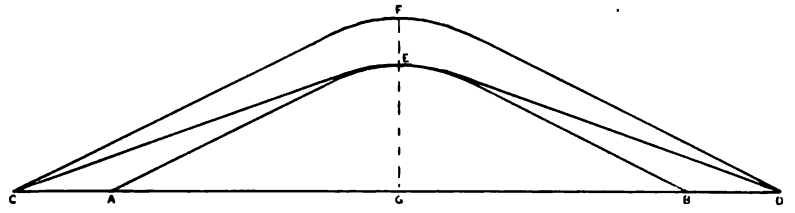

Figure 2.—Diagram to illustrate adjustment of drainage in rocks of varying degrees of resistance.

If we consider two slopes of equal altitude (EG, Fig. 2) and

unequal bases (CG and AG), the horizontal distance (AG) of the steeper slope will be less than that of the other slope (CG). If the slopes CF and CE have CG in common, and the grade of the first is greater than that of the second, then the altitude of the first (FG) must be greater than that of the second (EG).

From this it follows that in regions of rocks of varying degrees of resistance, either the main stream channels will lie nearer (horizontally) to the summits of the harder rocks, the summits remaining at a uniform altitude, or else, the horizontal distance of the summit from the stream being the same, slopes are developed by a differential lowering of the summits. The adjustment by either of these methods is usually modified through the development of the minor drainage lines. The tendency is always, of course, to attain the desired end by the simplest means.

Similarly, along the minor streams, graded slopes may be attained in one or both of the following ways. If the spaces between streams of the same class are the same in both hard and soft rocks, then to attain graded slopes the stream cañons in the harder rocks must be relatively deeper than in the softer rocks; or, in other words, the minor ridges must be at a greater elevation above their stream beds. If the depth of the cutting is relatively no greater in the hard than in the soft rocks, then graded slopes may be attained only by having the streams more numerous in the hard than in the soft rocks—that is, horizontally nearer their divides (as explained above for the main streams) and therefore closer together. Further, on account of the steeper grades in the harder rock, the branch stream courses will be shorter, in general, than those in the softer rock, with equal vertical range in the two cases.

From the above it follows that in the less resistant rocks the slopes will be less dissected than in the more resistant. The slopes will also be gentler, the summits and the intervening valleys broader, and the latter frequently shallower, in the areas of softer rocks as compared with those of harder. These more rounded and open forms will be contrasted with the more sharply incised forms and steeper slopes found in the areas of more resistant rocks. On account of gentler slopes, as well as on account of less resistance to weathering, the soil will be heavier in the areas of softer rocks, and, generally speaking, a more abundant vegetation will be found

in these areas, provided, of course, that other conditions are favorable to its growth.*

These results refer, of course, to areas of some size, where the stream courses are free to develop. The erosion of small areas of soft rocks in larger areas of hard ones, or *vice versa*, is more or less affected by the erosion of the surrounding areas. Saddles and valleys tend to develop in the soft rocks, while in the hard rocks bordered by softer ones are formed peaks and ridges which stand above the average altitude of the softer area. Erosion in these smaller areas probably tends more to differentiation of altitude than where the areas are larger. Even in the larger areas there is more or less tendency to differentiation, but this is not usually sufficient to destroy the effect of a generally even sky-line. The result of erosion, as seen in mature forms, is a greater or less differentiation of upland altitudes when viewed in detail, with, however, in ordinary cases, an impression of uniformity when taken as a whole.

In areas well differentiated by erosion, where the drainage is all subsequent, there may be a subequality of summits, due to the fact that the more resistant rocks then form the peaks and ridges, while the less resistant form the valleys. With the tendency to uniformity in the resistance of the rocks of the uplands, there would be a greater reason for uniformity of altitude. This, however, appears to be a point of minor importance.

Graded streams cutting in both hard and soft rocks do not cut vertically, on the whole, any more rapidly in one than in the other. For, since the parts are all interdependent, the cutting at one point can not be, on the whole, any more rapid than the cutting at all points in the stream course. There will be differential erosion, but only to a minor extent. The profile of the graded stream, while it shows irregularity in detail, will present simple uniformity when taken as a whole.

* From the general principles here given the roughly equal spacing of the principal rivers of a topographic unit, in even a mature region (see Shaler, loc. cit.), will follow as a necessary corollary. The spacing of the minor drainage lines in areas of rocks of differing degrees of resistance may differ somewhat; the streams will be generally closer together in the areas of harder rocks, other things being equal, but in either the harder or the softer areas, considered alone, the spacing for streams of the same class should be practically uniform

In the same way, in the divides formed in both hard and soft rocks, the cutting in neither can be of indefinite extent. For, as the stream can cut only as the slopes and summits are lowered, so the summits are lowered only as the stream cuts. As in the case of the stream bed, then, there will be differential erosion, and this will be greater in extent than that found along the stream itself, as would naturally follow from the principles already laid down. Monadnocks will be developed in the rocks of unusual resistance, and the areas of least resistant rocks may sink considerably below the general level. But with all this the differentiation will be limited—the maximum, which can not be exceeded, being determined mainly by the differences in the angles assumed by the various rocks—and will be apparent mainly in detail. The effect of the whole, as in the case of the stream profile, will be one of more or less uniformity, giving an evenness of the upland sky-line. The differentiation due to erosion will increase progressively to a maximum at maturity, beyond which it will decrease until (theoretically) it disappears entirely in extreme old age.

As a corollary to the above it may be stated that, at the beginning of a cycle of erosion, and throughout its earliest stages, the uplands will be formed by surfaces belonging to the time just prior to the opening of the cycle. Thus, flat-topped hills or ridges, showing pronounced truncation (provided they do not form a part of the graded slopes) may be unhesitatingly classed as not belonging to the existent cycle of erosion, but as remnants of older forms. This applies especially in cases where both hard and soft rocks are truncated indifferently. In such cases the more resistant rocks will preserve the truncated character for a longer time than the softer ones.

If at the beginning of the cycle of erosion the upland sky-line is markedly irregular—a condition of things which is the exception rather than the rule—it will depend on circumstances whether or not the uplands will tend to approach uniformity of altitude after graded slopes have been attained. Among the main factors determining the result are the character of the development of the matured drainage lines, the difference in original elevation, and the amount of variation in the resistance of the rocks. With great original diversity there may be no tendency to uniformity till old

age. Any marked uniformity in the final result in such a case would, of course, be due to peneplanation.

Orogenic Movements.—The formation of mountain ranges, the geographical units with which we have been dealing, takes place commonly by folding or faulting, or both, along lines of weakness, which are oftenest parallel to the continental margin. The *general* movements which form mountain ranges, since they are likely to be more or less uniform throughout the geographical unit, tend to uniformity of upland outlines. So, generally speaking, these movements would result in diversity of altitudes only when such diversity already existed in the region undergoing disturbance. For example, the uplift through faulting of the Sierra Nevada Mountains, which constitute such a unit, has not disturbed the uniformity which existed before, and which is still seen on the western slopes of the range.

On the other hand, *local* orogenic movements, since they tend to deform the parts of a unit, are likely to result in diversity of altitudes. Some so-called monadnocks may be due to this cause. Since, in general, according to the views already expressed, erosion does not tend, on the whole, to marked irregularity of upland features over large areas, it would seem that where such irregularity exists, it must be attributed mainly to local disturbances. To a minor extent, diversity of upland altitudes, or serration of crest lines, is produced by alpine glaciation. This, however, like ordinary stream erosion, affects rather the detail than the general result.

"*Tilting.*"—As we go down stream the volume of the stream increases, and the valley usually widens, owing to lateral corrasion, while the grade of the channel decreases. The neighboring graded slopes, however, still have an angle approximating those found at greater altitudes along the stream course (provided, of course, that they are in rocks under similar conditions as regards resistance, attitude etc.). The reason for this is that, as we go down stream, vertical corrasion is more or less replaced by lateral corrasion, which, by cutting away the base of the slopes, increases their grade near the bottom, and thus ultimately over the entire surface. Lateral corrasion is thus fully as effective as vertical corrasion for

lowering the summits of the adjacent slopes, and as the latter is replaced by the former, the adjacent graded slopes are able to maintain a similar angle.

If, on the whole, the rate of vertical corrasion decreases progressively as one goes down stream (see page 165), till it reaches zero at sea-level, then, if the cutting were wholly vertical, with decrease in its rate, the adjacent slopes must present decreased angles, other things being equal. With decrease in the angle of slope there must be also a decrease in the vertical distance between the stream channel and the adjacent ridges; thus the altitude of the ridges will decrease more rapidly than the altitude of the stream beds. When the vertical is replaced, in greater or less degree, by lateral cutting, the altitude of the divides tends to decrease still more rapidly. For since, as shown above, the lateral cutting is as effective as the vertical in lowering the summits, the result is the same as if the stream channel continued to be deepened by vertical cutting, and the altitude of the divides followed the descent of this hypothetical stream bed.

Professor Davis makes the criticism that "tilting has no announced place in Professor Tarr's theory;"* but there is no necessity for introducing tilting if the features in question can be as well explained without it. An application of the principles already given will, I think, sufficiently account for the relation of upland and stream profile, which is commonly ascribed to tilting of the region. Assuming for purposes of discussion that "a rough equality of mountain heights" has been established, then, "the master streams having gained a graded slope," with the erosion on the slopes following the cutting of the streams, we might expect, *other things being equal*, to find the elevation above the stream bed of all points along the divide roughly the same. But it has been already shown that as between the lower and upper stretches ("coast" and "interior" regions) of a stream, other things are not equal. "The streams are larger and the valleys are necessarily lower and broader near the coast than in the interior,"† and "the interstream uplands are," therefore, *not* "under essentially similar

* Loc. cit., p. 237.

† Ibid.

conditions in the two regions;" for the breadth of the valleys in their lower reaches implies that the bases of the slopes have been cut back by lateral corrasion, and the effectiveness of this method of reduction of interstream uplands has been indicated above.

According to the explanation of beveling given here, it might be expected in mature regions even of horizontally bedded rocks, which may give more or less flat-topped ridges, that the strata will be beveled going down stream. In fact, there should be beveling of the edges of the strata in all cases where the streams and ridges cut across the bedding of the rocks, except where the dip of the rocks is in the direction of the flow of the stream, and at an angle corresponding closely to the grade of the channel.

Soil.—In regions of active erosion, depth of soil appears to be more largely dependent on slope, climate, character of the subjacent rocks and of the vegetation, than on elevation. I have seen many instances of very thin soils among the mature forms of the Coast Ranges of California, at very low altitudes. On the other hand, I have recently had occasion to observe, in the Sierra Nevadas, a striking instance of deep soil at a comparatively high altitude—about 4,500 feet. The area is on a gentle slope, and in such a position that the surface could not well be assumed to be a part of an old peneplain, although in a region of generally even sky-line. In a shaft which had been run to a vertical depth of fifty feet below the surface, no solid rock had been reached. The soil is due to decomposition of the rock (diorite ?) in place. This instance goes to show that a considerable depth of soil may occur elsewhere than at low altitudes, and without peneplanation of the surface.

It remains true, however, that deep soils widely distributed over the uplands, and more or less independent of rock character, may be taken as evidence in favor of a peneplain, when there is other sound testimony to the same effect. In the actual peneplain, river gravels should be widespread, and it would seem that their evidence should persist for a long time after the elevation and beginning of the dissection of the peneplain.

Vegetation.—There can be no question as to the effectiveness of erosion, even on vegetation-covered areas. If the streams continue to cut down their beds, the slopes must follow, sooner or later, no

matter how deep the soil or how dense the vegetation. In both young and mature regions, some of this soil removal may be by sliding of the land, particularly in seasons of great rainfall. Landslides are common in the California Coast Ranges, even on slopes covered with vegetation.

As commonly agreed, vegetation tends to decrease surface erosion by binding the soil together, thus making its removal more difficult, and checking sliding earth; by protecting the surface, in many instances, with a more or less complete mat of leaves etc.; by breaking the force of the falling raindrops and hindering their free flow after reaching the ground, thus not only decreasing the velocity of the flow at the surface and distributing its volume, but also decreasing its volume, by allowing a longer time during which the water may be absorbed by the soil; by keeping the surface soil comparatively porous, and thus facilitating its absorption of water. The erosion on the slopes being thus decreased by vegetation, if at the same time the cutting in the adjacent stream beds remains the same, the angle of the slopes must ultimately be increased, since, according to the principles already laid down, the erosion over the surface must keep pace with that in the stream beds. Vegetation may tend, therefore, to increase the angle of graded slopes,—a conclusion in direct opposition to the impression which seems generally to prevail, that bare slopes are always steeper than those covered with vegetation (other things being equal).

While vegetation tends to protect the soil from erosion, it tends also to greater soil depth, both by its binding of the soil, which prevents washing, and by the action of vegetable acids, conserved water, root penetration etc., leading to more rapid rock decomposition. With the increase in the depth of the soil, the readier erosion of soil as compared with rock will counterbalance, to a greater or less extent, the protection against erosion furnished by the vegetation. The rate of rock decomposition (due to the causes mentioned above) will increase until a maximum is reached, after which it will follow essentially the rate of wearing down of the vegetation-covered slopes.

Vegetation tends to a uniform distribution of the flow of water over the entire surface of the slope, and the surface erosion is there-

fore more uniform. That is, the dissection is not so great as in regions without vegetation.

If vegetation decreases erosion on a given slope, less material for cutting will be furnished to the stream at the foot of the slope. Whatever effect this may have on the cutting of the stream, a more important factor is the conservation of moisture in the soil, due to the vegetation, and the consequent decrease in the immediate amount of water given to the stream. This loss to the stream is partly permanent, the moisture being taken up by the plants and returned to the atmosphere, and partly only temporary, as most of the water not so taken up will be given up slowly to the stream. This retention of moisture tends to a smaller increase of the stream's volume just after a rain; and as it is the volume of water at the season of flood which is most effective in cutting, this influence is an important one in reducing the rate of the stream's corrasion. Widespread vegetation will, therefore, tend to decrease the rate of general erosion throughout a drainage system; while, other things being equal, the angle of the slopes covered with vegetation will be greater than that of any slopes not so covered.

CONCLUSION.

It has been already indicated that the explanation here given of planation forms is not intended to do away with the theory of peneplanation. Some of the forms described as peneplains must undoubtedly be accepted as such, in the established sense of the word; but it has, I think, been sufficiently shown that this hypothesis is one which should be employed with the utmost caution. For the many so-called peneplains which strain the theory beyond its reasonable limits, the hypothesis of "beveling," as proposed by Tarr, and modified by the present writer, is offered as an adequate and much more probable explanation.

The occurrence of a peneplain can not be predicated upon evidence of a "nearly featureless plain," alone. This must be correlated with all other available evidence before the cause of the planation can be assigned. If one were to find widespread truncation of the hilltops in a region of disturbed rocks, with adjusted stream courses, in addition to evidence of the "nearly

featureless plain," and to the occurrence of deep soils and residual gravels, there could be little chance of mistake in calling the surface a peneplain. Adjustment of the stream courses might be found in regions which had not reached the peneplain condition before elevation, but if found in conjunction with the other features just mentioned, it would form confirmatory evidence of the existence of a peneplain.

Thus, while, as has already been shown, most of the features of so-called peneplains may be explained in other ways, the occurrence of all of them *together* should be positive evidence of the existence of a peneplain. A truncation of the summits, at a roughly uniform altitude, with the occurrence of stream gravels here and there upon the uplands, little below the general level, would form strong presumptive evidence of peneplanation.* Systematic and widespread truncation of hilltops, in regions of disturbed rocks, where the bedding is beveled across, can be explained only by actual planation in some form, through either marine or subaerial erosion.

As to buried peneplains, even greater caution is necessary in pronouncing on the evidence, which in the nature of the case must be very meager. Most of the cases described as buried peneplains rest, in the opinion of the writer, on very doubtful evidence. It is to be noted that the buried peneplains described are never dissected, while those with which we are familiar on the surface are all dissected to a greater or less degree. This is only natural, as it would be almost impossible to determine a buried peneplain if it had suffered much dissection before burial, while those which were submerged without dissection might still yield definite evidence as to their character.

Further, the hypothesis of beveling is not intended to take the place of any other causes which may result in an effect of planation—such as horizontality of bedding, extensive lava sheets or

*It has been suggested to me by Professor Lawson that ***planation*** (see Gilbert: Report on the Geology of the Henry Mts., p. 121) might take place without an approach to ultimate base-level, by the meandering, at considerable elevations, of streams in soft rocks, above a local base level in very hard rocks. The evidence just described might indicate such a condition of things, since in itself it would be insufficient to determine whether or not there had been an approach to ultimate base-level.

delta deposits, or submarine abrasion. Even if beveling were substituted entirely for peneplanation it would not follow (as Professor Davis asserts *) that plains of marine abrasion would be discarded as well. The question as raised by Professor Tarr is one of causes rather than of results; and because one cause is discarded, it by no means follows that similar results due to another cause are discarded along with it.

Finally (as already suggested, p. 156), in accounting for many instances of the uniformity usually expressed by the term peneplain, it is quite possible that a combination of two or more of the available explanations may be called for. An intelligent opinion can be formed, in many cases, only after a study of the geology in connection with the topography of the region. No broad general rule can be laid down, but each field must be interpreted by itself.

University of California, October, 1899.

* Loc. cit., p. 233.

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A TOPOGRAPHIC STUDY

OF

THE ISLANDS OF SOUTHERN CALIFORNIA.*

BY

W. S. TANGIER SMITH.

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Introduction.—The islands off the coast of southern California furnish an unusually interesting field for physiographic study, both on account of the isolation of the individuals, and on account of the pronounced variation of form presented. This paper points out and discusses the causes of their principal variations, giving, at the same time, a brief outline of their most recent movements,

*The following paper was first prepared for publication in April, 1897, but was withheld for various reasons, the chief of which was the author's desire to give more careful study to the subject than had been possible at that time. He has not yet had opportunity to make such further study in the field as he desired, but after a careful review of all the facts at his command, he feels that the paper should be presented as it stands, leaving the corroboration or disproof of his views to future investigation. The paper was read in abstract at the December (1899) meeting of the Geol. Soc. Am., Cordilleran Section.

as indicated by the topography of the islands and neighboring mainland.

Grouping of the Islands.—These islands, which range in length from a fraction of a mile to nearly twenty-five miles, fall geographically into two groups, a northern and a southern. To the former belong the islands of San Miguel, Santa Rosa, Santa Cruz, and Anacapa, lying in a nearly straight line and separated from each other by only narrow channels, and from the mainland by the Santa Barbara Channel. The islands of the southern group are San Clemente, Santa Catalina, Santa Barbara, and San Nicolas, with Begg's Rock, which stands in the relation of a very distant off-shore

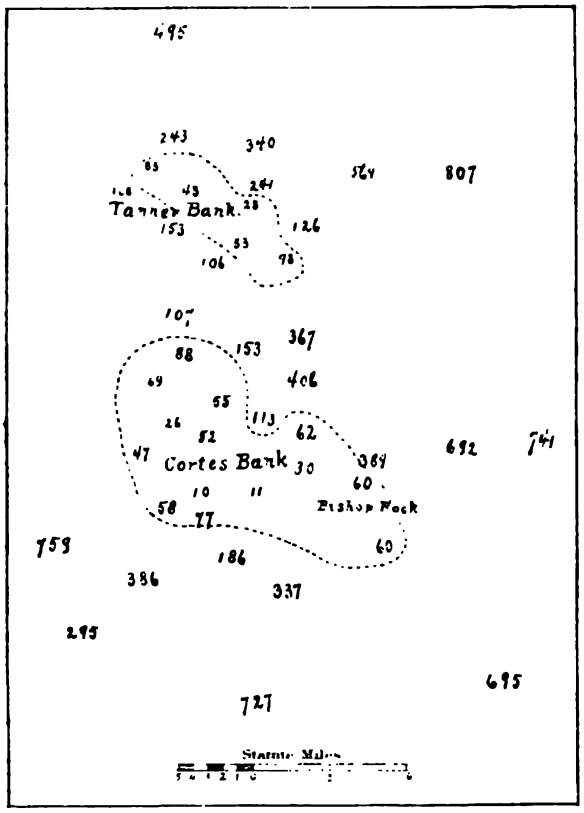

FIGURE 1.—Cortes Bank and Tanner Bank, former islands, truncated by wave cutting in post-Pliocene times. The soundings are in fathoms

stack to San Nicolas. These four islands are widely separated, but each one of them, as well as the group of northern islands as a whole, has a general trend parallel to that portion of the coast to which each is nearest. A submergence of the coast of 100 feet would add to the southern group of islands San Pedro Hill, situated on the main coast to the north of Santa Catalina; while a minimum elevation of about 175 feet would add to the group as islands what are now three submarine elevations known as Cortes, Tanner, and Osborn Banks. Cortes Bank is situated about forty miles southwest of San Clemente, Tanner Bank lying about ten miles to the north of Cortes Bank (see fig. 1). Osborn Bank lies about five miles south of Santa Barbara Island, and has a northwesterly and southeasterly trend, which, like that of the islands in general, is roughly parallel to the neighboring mainland coast.

Besides the islands already named, there is a small group, Los Coronados Islands, about ten miles off the coast of San Diego county. An elevation of the coast amounting to 175 feet would join this entire group to the mainland. On account of their size and situation, these islands will not be further considered.

Only San Pedro Hill, Santa Catalina* and San Clemente Islands have been visited by the writer. The information concerning the other islands is therefore indirect, gleaned in small part from the meager notes which have been published concerning them by the Geological Survey of California, the California Academy of Sciences, and in the various annual reports of the State Mineralogist. Nearly all of what follows, however, is based on a study of their topography as shown on the charts of the United States Coast and Geodetic Survey.

The islands may be divided topographically into two groups, independently of their geographical arrangement. The one group has simple topography, with comparatively gentle slopes and moderate or slight dissection; the other has rugged, sharply

*The study of Santa Catalina (see Proc. Calif. Acad. Sci., Third Series, Geol., Vol. I, No. 1, 1897) was made independently, without any attempt to correlate its features with those of the neighboring land areas. Further investigation has led to some modifications of the views therein put forth, as indicated by the statements made in this paper.

incised and serrated forms. The differences are dependent in part on differences in topographic age, and in part on differences in the character of the rocks.

Topographic age is estimated by the amount and character of the contrast due to subaerial erosion, allowance being made in this estimate for differences in the resistance of the rocks to such erosion. Where the rocks are hard, the contrasts will be greater, the subaerial slopes less gentle and the topography more rugged, for a given stage of development, than where the rocks are less resistant. The influence of marine abrasion as a factor in determining topographic age depends upon circumstances. Given an isolated elevated mass, standing on a coast line, or forming an island, wave action, by decreasing the volume of the mass, aids subaerial erosion in bringing the elevation nearer the condition of ultimate base-level, and in this way tends to increase topographic age. On the other hand, when a coast line is depressed, wave action tends to obliterate the contrasts produced by previous subaerial erosion, and to simplify the general topographic form. Therefore, on re-elevation, the youth of the topography will have been renewed, to a greater or less degree, so far as the surface has been brought within reach of wave action.

The forms of the Coast Range, in general, approach maturity, and are characterized, for the most part, by narrow ridges and V-shaped valleys. It is generally held by Pacific Coast geologists that these forms belong mainly to the period of erosion following the close of the Miocene, the land then standing at a greater elevation than now.

Although the coastal forms are, on the whole, quite rugged, there are many variations in the amount and character of the dissection, due mainly to differences in the resistance of the rocks from which the topography is carved. Some of the forms in the less resistant rocks, especially where isolated, present, comparatively, very gentle slopes, and are not deeply dissected, although the forms may still be called mature for that particular rock. Along the immediate coast line the more rugged topographic forms do not appear to have been greatly modified by wave action in post-Pliocene times; the less resistant the rocks, the gentler the

lopes and the less the contrasts due to subaerial erosion, the greater as been the modification.

Most of the islands of southern California present forms similar o those found along the mainland coast, with the variations which ould naturally result from the differences in the resistance of the ocks, and the possible modification of the forms by wave action uring progressive elevation. For this reason it is believed that ost of the islands (among which it is intended to include San edro Hill, throughout this paper) possessed nearly mature topography at the close of the post-Miocene period of erosion, this aving since been more or less modified (especially in the case of hose islands with less resistant rocks) by wave action, and to a less xtent by Pliocene and later deposits.

Two of the islands with simple topography are exceptional in resenting extremely young topographic forms, their masses not aving been elevated till after the close of the post-Miocene erosion eriod. One of these islands, San Clemente, is developed in hard, he other, San Nicolas, in soft rocks.

The rugged forms along the coast and among the islands are lways nearly mature and developed in rather resistant rocks. The imple forms, however (as indicated by what has been already iven) are either (*a*) very young, in either hard or soft rocks, or (*b*) riginally mature, or nearly mature, forms, in soft rocks, modified, o a greater or less extent, by later deposits and by wave action. his latter class now presents forms which range from those near outh to those well advanced toward maturity, depending on the mount of modification of the original form.

Classifying the islands on the basis already given, we have elonging to the group with simple topography: San Clemente, ith extremely young topography in generally hard rocks; San icolas, with young topography in soft rocks; San Pedro Hill, ith modified mature topography, now presenting, on the whole, he forms of adolescence, developed in moderately soft rocks; San iguel, with modified mature topography, now rather youthful in haracter, developed in soft rocks; also Santa Rosa, in part, shows odified mature topography, though belonging, according to its eneral character, with the more rugged islands.

To the group with rugged topographic forms belong Santa Catalina, Santa Cruz, and the larger part of Santa Rosa. Santa Barbara and Anacapa Islands are of doubtful grouping, owing to their small size.

It is probable that all of the islands originated through crustal deformation, for the most part as tilted blocks, though with the information at present at hand, it can not be definitely asserted for them all. San Clemente and San Nicolas are without doubt faulted blocks; and Santa Catalina seems to be, in part at least, due to faulting. San Miguel and Santa Rosa, with a minimum depth of water of not more than 100 feet between them, would appear to be a single faulted block, probably modified by differential movements within the mass. Whether the remaining islands of this northern group, Santa Cruz and Anacapa, which apparently form a single unit, originated at the same time and in the same way as San Miguel and Santa Rosa, future field work alone can decide. The remaining island, Santa Barbara, shows no block-like character.

Description of the Islands with Simple Topography.—Of the islands of the first group, San Clemente has been described by Dr. Lawson* and the writer† as a tilted orographic block. It is characterized by gentle slopes on the seaward side and abrupt slopes on the landward side. The seaward slope is marked by an unusually well defined series of terraces, up to an altitude of about 1,500 feet;—a series which (for reasons given later) is unequaled elsewhere on the California coast. On the landward side only fragmentary terracing occurs, where the slopes are locally comparatively gentle, as toward the northwestern end, where the rocks are folded rather than faulted. Along the steeper parts of this side not even traces of terraces are to be seen.

The rocks of the island are for the most part hard volcanics, only a small proportion consisting of less resistant sedimentary deposits.

The drainage of San Clemente Island is of post-Pliocene age,

*The Post-Pliocene Diastrophism of the Coast of Southern California, Bull. Dept. Geol., Univ. Calif., Vol. I, No. 4, 1893, p. 129.

†A Sketch of the Geology of San Clemente Island, 18th Ann. Rept., U. S. Geol. Surv., 1896–97, Pt. II, p. 467.

d is still in its infancy. It consists, on the southern side—where ll developed—of long, trough-like forms, having a general direc- n at right angles to the trend of the island, and separated by)ad stretches of undissected, terraced surface. Some of the annels on this side of the island scarcely more than notch the races over which they flow; few have cut down to sea level. A all lagoon is formed near the mouth of at least one stream, ar the southeastern end of the island, which has cut its channel, its lower reaches, in soft Miocene shale, and in a region of nsiderable shore drift. The drainage of the northern slope nsists of numerous short, steep-graded streams, which have)red this side of the island, in the steeper and higher parts, with nparatively shallow valleys.

The description of the general topographic features of San :mente would apply, with little modification, to San Nicolas, iich lies to the northwest of it. San Nicolas differs mainly in e, and in having its fault scarp facing the ocean instead of facing : land. The island is nearly nine miles in length, with a .ximum width of three and three-quarters miles. Its highest int is 890 feet in altitude, and lies in the ridge which extends : whole length of the island, nearer the southern side, at an :rage distance of a mile from the shore. The rocks of the ınd are sandstone (according to Dr. Cooper‡ and Dr. Stephen wers†), and are therefore readily weathered. Bowers gives the) as northerly, about 13° to 15°.

The gentle slope of the island is toward the north, and this e is distinctly terraced. So far as known to the writer, however, definite terraces occur on the southern and more exposed side, ıere, if the development of terraces depended on the power of the ves alone, we should most expect to find them. Cooper‡ has :ntioned three "raised beaches" on the island, at elevations of , 80, and 300 feet. The flat-topped summit, also, is without

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* Geol. Surv. of Calif., Geol., Vol. I, 1865, p. 184.

† Calif. State Mining Bureau, 9th Ann. Rept., State Mineralogist, for 1889, 57.

‡ Loc. cit.

doubt due to terracing. San Nicolas must have been at one time higher than at present, the island having been completely cut away at one stage in the coastal uplift. The same thing is now, again, taking place; for, judging from the submarine shelf on the northern side, the greater part of the island has been cut away in recent geological times, and were the present rate of cutting to continue, it would not be long before the whole of the island, with its records of earlier terracing, would be planed off. (Cortes, Tanner, and Osborn Banks are examples of islands whose tops have been wholly removed during the recent stages of wave-cutting. They will be treated more fully later, under the head of submarine features.) The small number of well-developed terraces found on San Nicolas as compared with the number on San Clemente may be accounted for by rapid cutting in the soft rocks forming this island, the cliffs on the terraced side having been cut back so rapidly that many of the previously-formed terraces were wholly obliterated.

The drainage of San Nicolas is much like that of San Clemente. Numerous steep-graded channels score the shorter slope of the island, tending to the formation of cirques; while few, long, narrow and apparently shallow troughs characterize the northern slopes. There are a few indentations on the northern coast, but it is probable that none of them represent drowned valleys of the present cycle of erosion.

That the island is a faulted block needs little more proof than its form, which is as definitely that of a tilted crust-block as is that of San Clemente. Below sea-level the contrast between the two slopes is even greater than in the case of San Clemente.

The topography of the island has been called young. This conclusion is based not only on the character of the chiseling due to subaerial erosion, but also on the apparently slight modification of the fault scarp,—a striking feature, in view of the fact that the island is composed of soft sandstone, and faces the open ocean, and, therefore, the direction of greatest waves. The abruptness of the fault scarp can not be due wholly to rapid wave-cutting, for the submarine contours show only a comparatively small amount of wave-cutting on this side of the island, and the high angle is

continued below sea-level to a depth of at least 300 fathoms.

Begg's Rock, forty feet in height, and lying nine miles northwest of San Nicolas, has been already spoken of as a distant off-shore stack belonging to that island. It lies within the 300-foot submarine contour.

San Pedro Hill has been described by Dr. Lawson.* It has a length of about nine and a half miles, and an average width of nearly five miles, its highest part having an elevation of 1,482 feet. The rocks of the hill are largely Miocene shales, and are characterized by rather gentle subaerial slopes, showing moderate contrasts due to dissection. The forms of San Pedro Hill, like those of the Coast Range in general, were doubtless mature previous to the Pliocene depression of the coast. These matured forms have been modified by wave action, which has given rise to a series of well-developed and well-preserved elevated terraces. This modification of the subaerial forms has been greatest at either end of the hill. Near the middle of the hill on the seaward side, and on the landward side, the modification has been least, and the conditions most nearly approach the original mature forms. The valleys due to dissection are not deep, nor would they ever, it is probable, become large and open, on an isolated hill of this size, and in rocks of such a character, during the complete physiographic cycle. Considering the softness of the rocks of which the bulk of the hill is composed, the general effect of the topography is seen to be at least that of adolescence. The great terraces on the seaward flanks of the hill are still fresh and young, *as terraces*, but the topographic age of the surface as a whole, that is, its progress from infancy to old age, is fairly well advanced.

San Miguel, the westernmost island of the northern group, lies about twenty-six miles from the mainland, and about three and a half miles west of Santa Rosa, from which it is separated by San Miguel Passage, with a maximum depth, in the middle, of less than 100 feet. So shallow are the channels between all the islands of this group, that an elevation of from 160 to 180 feet would make a single island of them all.

*The Post-Pliocene Diastrophism of the Coast of Southern California, Bull. Dept. Geol., Univ. Calif., Vol. I, No. 4, 1893, pp. 122–128.

San Miguel has a length of about eight miles, and a width of about four. Its two principal peaks, 861 and 850 feet in altitude, respectively, are situated near the center of the island, and separated by a saddle. From these points the surface slopes gently in all directions. Steep cliffs mark the southern side of the island, rising to a height of from 400 to 600 feet along the middle of this side. For a distance of over three miles on this side there is a low and rather broad platform, the rear of which has an elevation of only forty to eighty feet.

The summit of the island is nearer the southern side, and the longer and gentler slopes are to the north. This side of the island is but slightly dissected, and shows only three definite stream courses for its entire length. Since the gentler slopes face the north, and since the open ocean is on the west, we should expect, on the principles set forth later, to find the greatest amount of cutting on the west and northwest; and, judging from the submarine contours, this is the case. For the same reason, the best developed elevated terraces, if any are to be found, must be looked for on the same part of the island. The small U. S. C. & G. S. map has rough indications of terraces on the northern side of the island, besides the low platform on the southern side, and a suggestion of terracing near the eastern extremity. On the large contoured manuscript map of the U. S. C. & G. S. (scale 1:20,000) this apparent terrace at the eastern end is seen to be at an elevation of 240 feet. North of the island's center, terrace-like platforms are seen at elevations of 440–480 feet and 520–600 feet. The most pronounced terrace-like structures, however, lie along a line running from the western summit toward the western end of the island. Along this general direction there are nearly level stretches at 220–240 feet, 320 feet, 480 feet, and 560 feet. At 320 feet the nearly level area has a width from front to rear of over a mile; the interval between the 440- and 480-foot contours is three-quarters of a mile, and that between the 520- and 560-foot contours is more than half a mile. In all cases these level stretches are marked by a more rapid rise at their rear. These features certainly simulate terracing, and although the above facts are not sufficient for an absolute statement, there is little doubt in the mind of the writer, especially

in view of the general topographic character of this side of the island, that these are true raised beaches, cut in very slightly resistant rocks, and their outlines softened by erosion. For purposes of the present discussion this will be assumed to be true.

Drifting sand is indicated on the map, at the western end of the island, for a distance of about a mile and a half towards the summit; also, to a less extent, at other points. These æolian sands would naturally tend still further to render any terrace features indistinct; but evidently this factor, even in combination with the ready erosion of the rocks, has not been sufficient entirely to destroy the terraced character of the topography.

The abrupt cliff on the southern side of San Miguel (forming the sea-cliff for the western half of this side, and marking the rear of the 40–80-foot terrace for the eastern half) may or may not be genetically a fault scarp; but its height and abruptness are due, in part, at least, to wave action, undercutting previously formed terraces, and eating back into the base of the cliff. This conclusion is based on the breadth of the submarine platform on this side of the island, and on the presence of an elevated terrace. Whatever terraces may have been previously formed on this side of the island, were obliterated by the cutting which developed the 40–80-foot terrace, just as this terrace, in turn, has been largely destroyed by the most recent cliff cutting.

The Rugged Islands.—Of the islands of the second group, a description of the features of Santa Catalina has been given elsewhere by the writer.* The main characteristics are the mature and very rugged topography, developed in generally resistant rocks (mainly quartzites and igneous rocks); the leveled character of the summit, at an average altitude of 1,500 feet; the drowning of many of the stream valleys, particularly the largest, at their mouths; the terraced character of the Little Harbor region, this region representing an older, structural valley (with gentle slopes), a continuation of which is shown by the submarine contours; the apparent absence of terraces elsewhere.

One of these points—the apparent absence of terraces—needs

*The Geology of Santa Catalina Island, Proc. Calif. Acad. Sci., 3d. Series, Geol. Vol. I, No. 1, 1897.

further comment. In a foot-note in the above-mentioned description* the writer mentions the occurrence of rolled pebbles near the southeastern end of the island, at altitudes of 1,000 and 1,400 feet, but considers their character doubtful. It is possible that these rolled pebbles are not shore deposits, but it seems now to the writer hardly probable, especially in the case of those at the 1,000-foot level, which rest on a terrace-like portion of one of the branch ridges running from the main ridge. This branch ridge and the others near it have a roughly terraced character at several points. On the ridge where the pebbles were found, such benches occur at 800 feet, 1,000 feet, and 1,060 feet. The 1,060-foot bench is one of the most pronounced of these, and it agrees pretty closely with the altitude of the corresponding notches on the neighboring ridges. As determined by a hand-level, this bench was a very little lower on the ridge to the north, and a little higher on the ridge to the south, than on the ridge where the pebbles are. On another minor ridge about a mile to the south of this, notching was seen at the altitudes 865 feet, 1,060 feet, 1,300 feet, and 1,400 feet, as determined by aneroid. These benches are not very pronounced, especially as they occur on sharp ridges where they would more readily suffer obliteration than on little dissected surfaces. It is of course possible that some of these readings do not represent definite former ocean levels, but, taking all the evidence into consideration, it is improbable that some of them are not true terraces.

Further evidence to the same end is to be found in the planation of the summit of the island (in addition to the terracing of the Little Harbor region, already mentioned). This character has been ascribed by the writer† to peneplanation; but more mature consideration has convinced him that it could be due neither to peneplanation nor primarily to beveling‡, but that it must have been caused mainly by marine abrasion during a depression of the island, and after the present topographic forms had been largely developed.

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*Loc. cit., p. 12.

†Loc. cit., p. 69.

‡See, Tarr, The Peneplain, Am. Geol. Vol. XXI, June, 1898, pp. 351–370, and, Smith, Some Aspects of Erosion in Relation to the Theory of the Peneplain, Bull. Dept. Geol., Univ. Calif., Vol. 2, No. 6, 1899, p. 162.

(In support of this view it may be mentioned that a patch of loose water-worn pebbles was observed at one point on the main ridge near the eastern end of the island.) The summits over the larger part of the island were planed away, leaving a small and nearly centrally situated nucleus, now shown in the two prominent peaks a little to the east of the center of the main division of the island.

Some of the canyons furnish further evidence as to the later movements of the island. The rugged topographic forms of Santa Catalina are, without doubt, of the same age as the coastal forms; that is, mainly belonging to the post-Miocene interval of erosion. In a number of the canyons deposits were formed which have been cut into by the present streams. One of these canyons is a tributary of Avalon Canyon, having a length of about one and one-half miles, with a fall in the stream bed of about 1,300 feet in that distance, thus giving a steep-graded stream, and for the greater part of its length, a narrow, V-shaped canyon. Up to an altitude of 250 feet (as far as it was followed by the writer) the stream has been cutting through earlier deposits to a depth varying from three to eight feet. How much higher the same thing may be found, is not known. Between the altitudes of 150 feet and 175 feet the deposits had a width of about forty feet at the surface (in the narrow, V-shaped canyon), and a maximum thickness of about eight feet. In the center of this deposit the present stream had made a narrow cut several yards in width, and, at most points, down to bed-rock. Practically no impression had been made on the underlying rocks, thus indicating the short time that the stream has been cutting since the deposits were laid down. The rocks do not vary greatly in character for the entire length of the stream course, and, so far as known, there has been no barrier to cause deposits in the bed of the channel. The only satisfactory explanation, therefore, is that of depression since the canyon was cut, followed by elevation causing renewed cutting. This later elevation was prior to the depression which caused the drowning of Avalon Canyon at its mouth.

In another V-shaped canyon, in the Little Harbor region, at an altitude of several hundred feet, the present stream has cut through an earlier stream deposit to a depth of about twenty-five feet. At two other points in this same region, but in the broader parts of

the canyons, similar cutting in earlier deposits has taken place, to about the same depth. The upper limits of the deposits in the Little Harbor region were not determined, but they were noted up to about 300 feet.

Santa Rosa, the second in size of the islands of the northern group, is roughly rhombic in outline, with a length of about seventeen miles, and a width of about eleven. Its main watershed connects the eastern and western extremities of the island, bending to the south, and lying considerably nearer to the southern than to the northern coast throughout its length. The minor ridges have a general radial arrangement about the central portion of this divide. That portion of the main divide which forms the island's crest is a little to the southwest of the center of the island, and runs in an easterly and westerly direction. This region has an average altitude of a little over 1,500 feet, a height not even approximated by any other portion of the island. The main ridge here is almost level, having a variation of not more than seventy-five feet for a distance of over three miles. In nearly four miles the variation is less than 175 feet. It would thus appear that Santa Rosa, like Santa Catalina, has suffered planation at an altitude of about 1,500 feet.

The southern half of Santa Rosa is quite rugged, with topographic forms closely resembling those of Santa Catalina. In the northern half the summits are broader and platform-like, the general slope is gentler, the relief not so marked, and the whole character is that of forms cut in much softer rocks than those of the southern half. The effect of the whole is of mature topography, the differences being due to differences in the rocks. The softer rocks are less resistant than those of San Pedro Hill, if the character of the dissection may be taken as a criterion. The forms of the northern half, as in the case of San Pedro Hill, have doubtless been more or less simplified by wave action. The topographic age is believed to be not far from maturity for such soft rocks. The general form of the island as a whole is suggestive of a faulted crust-block, though considerably modified by erosion.

According to the principles set forth later, pronounced terracing, if it occurs at all, would be looked for only on the gentler,

northern slopes of the island. On the small hachured map (U. S. C. & G. S.) of Santa Rosa, the appearance of this half of the island is that of a platform dissected by numerous streams flowing in comparatively open valleys. It would seem that these platform-like areas could be ascribed only to marine action, either deposition or abrasion or both. No very decided indications of terraces, however, appear on the map for this part of the island, except close to the northern shore. At the western extremity and at various points along the northern shore a narrow elevated terrace appears, of the marine origin of which there can be little doubt. The main ridge descends gradually from the island's crest to the northwest, and along its course are found several nearly level stretches. At about 1,000 feet the ridge is nearly level for over a mile; the interval between the 540- and 580-foot contours, along the ridge, is more than half a mile, while that between the 420- and 440-foot contours, near the western extremity of the island, is a mile and a half. The forms near this western extremity are probably more or less modified by drifting sand, as indicated on the small map.

Santa Rosa faces the mainland, which is distant only about thirty miles, so that the waves on the landward side have not the sweep that they have in the case of San Nicolas, distant about sixty miles from that part of the coast which it faces. In the case of both islands, the waves from the open sea can strike the northern coast only at a considerable angle. Judging from the submarine contours, the greatest cutting in the case of San Nicolas is on the northwestern extremity, where a low angle of slope is presented toward the open sea. The same is true of San Miguel Island, to the west of Santa Rosa; and the cutting in the case of Santa Rosa would doubtless be more pronounced were it not that the western end of the island is somewhat protected from wave action by San Miguel.

Santa Rosa has one broad and open bay, which is not connected with the present stream valleys of the island. There are no bays at the mouths of the present stream valleys, comparable in size to the harbors at Avalon and at the Isthmus on Santa Catalina, but this is apparently due to a lack of valleys of sufficient size and development. The same thing is true of Santa Cruz Island. Small bays

similar to the coves of Catalina are found on Santa Rosa at the mouths of a number of the stream valleys, and present evidence of submergence as unmistakable as in the case of Santa Catalina. Lagoons, also, are to be found at the mouths of several of the stream courses, where drifting sand is abundant.

Santa Cruz Island, a little to the east of Santa Rosa, is the largest of all the islands of the two groups. It consists, like Santa Catalina, of a larger and a smaller division connected by a narrow neck. The larger division, comprising about two-thirds of the length of the island, has an average width of six and a half miles, the narrower portion averaging about three miles in width. The total length of the island is a little over twenty-three miles. The smaller division, including the neck, has a prominent axis, having the same trend as this part of the island, and nearly centrally situated. It is crossed by a prominent transverse axis a little over three miles from the eastern end of the island. The western and larger division shows two principal ridges, running parallel with the general trend of the island. The northern and higher ridge extends the entire length of this portion of the island, and not far from its middle point is connected with the southern ridge. The latter at its eastern extremity is connected by a short spur with the axis of the smaller division. Along the length of the last two ridges, taken together, we find the following altitudes given for prominent points, on the small hachured map of the U. S. Coast and Geodetic Survey, 1,329 feet, 1,374 feet, 1,496 feet, 1,549 feet. On the northern ridge the altitudes 1,800 feet, 2,407 feet, and 2,144 feet are given. Unfortunately, the writer had access to no larger map of Santa Cruz than this (scale 1:200,000), so that no statement can be made as to the uniformity of altitude of the summits.

The northwestern part of the island presents topographic forms closely resembling those of Santa Catalina. The central, southern, and eastern portions, however, show few or no branches on the streams flowing from the main divides, the forms being long, simple, and trough-like. The effect of the whole is of a generally rugged, mature topography, developed in rather resistant rocks.

oodyear* states that more than three-fourths of Santa Cruz onsists of volcanic material.

The stream courses of Santa Cruz are well developed and umerous, and many of them show evidence of submergence at ieir mouths, in the formation of small bays. These flooded stream alleys are more numerous than in the case of Santa Catalina.

Nothing is known to the writer concerning possible terracing n Santa Cruz. From the character of the topography it is robable that, if any terraces do occur, they are not well-developed.

The chief characteristics of the second group of islands are: a igged topography; a drowning of many of the stream valleys when they are of sufficient size and development) at their mouths; n absence of pronounced terracing, which does not preclude, owever, some evidence of such features, where comparatively entle slopes have been exposed to vigorous wave action; and, in ie case of Santa Catalina and Santa Rosa, at least, a planation of ie summits at an approximate altitude of 1,500 feet.

The Small Islands.—Two islands remain unclassified,—Anacapa f the northern group, and Santa Barbara of the southern.

Although Anacapa is composed of three small islands, these re hardly to be separated, as they lie in a nearly straight line, with ery narrow channels between them. They are usually, therefore, onsidered as a single island. The group has a length of about five iiles, and a maximum width of a little more than half a mile. Vest Anacapa is the largest, and rises to a height of 980 feet. 'he chief features of the group are the abrupt cliffs on the south, ising nearly or quite to the summits of the islands, with gentler lopes toward the north. The cliffs are nearly continuous on all ides, but lowest on the north. The rocks of Anacapa are volcanic, ccording to Dr. L. G. Yates.†

According to Davidson's description and sketch,‡ Anacapa is

*Calif. State Mining Bureau, 9th Ann. Rept. for 1889, p. 155.

†Calif. State Mining Bureau, 9th Ann. Rept. for 1889, pp. 171–174.

‡The Abrasions of the Continental Shores of Northwest America, and the upposed Ancient Sea Levels, Proc. Calif. Acad. Sci., Vol. V, 1873–74, p. 93, nd Plate V.

terraced at an altitude of about 300 feet. Yates* speaks of finding rolled pebbles "on the table-land of Middle Island" and also at one point on Western Anacapa. As Santa Cruz and Anacapa are without doubt genetically parts of the same mass, it is probable that the movements indicated by the terracing of Anacapa were participated in by Santa Cruz.

The northern slopes of Anacapa are not marked by definite channels, except on the western island. Here there are several apparently shallow channels, one of which has a corresponding notch in the shore contour.

Santa Barbara has an area of about a square mile, and is roughly triangular in shape, with the base of the triangle toward the east. Parallel to this base, and about midway between base and apex, is the saddle-shaped main axis, from which the surface slopes gently to the east and west. The island is surrounded by cliffs, which reach their maximum height where they cut across the main axis. The eastern slopes are marked by a few small and shallow channels, but none are shown on the west. Cooper† states that this island shows three or four imperfect terraces. He mentions one in particular, on the eastern side, at an elevation of thirty feet, on which shells are found. This terrace is shown on the map as a narrow shelf at an elevation of forty feet (by the nearest contour). Other terracing, not so definite, is shown both on the west and on the east, at elevations of 180 feet and about 280 feet. Santa Barbara is 547 feet in altitude, and, according to the same authority, is composed of volcanic rocks.

Submarine Features.—Bordering the entire length of the California coast and closely following its general configuration, is a comparatively narrow submarine platform or terrace, with very gentle outward slopes, and its outer margin, in general, marked approximately by the 600-foot submarine contour. From the outer edge of this platform the descent to oceanic depths is at a greatly increased, though by no means uniform angle. This platform not only follows the general outline of the main coast, but is found surrounding all the islands of southern California. Its width is

* Loc. cit., pp. 172, 173.
† Loc. cit., p. 183.

variable. From Point Conception to San Diego it varies from a minimum of about a mile, to the southwest of Point Vincente, to a maximum of ten or eleven miles, found at several points. The usual width is from three to five miles.

Along the northern coast of California the descent from the platform just described to oceanic depths is without noticeable break (as shown by the few soundings on the published maps of the U. S. Coast and Geodetic Survey). Between Monterey Bay and Point Conception, however, there is in addition to this, which may be called the upper platform, a second and lower platform, more or less pronounced in its development, the outer edge of which is roughly marked by the 3,000-foot submarine contour. The distance of the 3,000-foot submarine contour from Cayucos is about 43 miles;* from Point Sal 40 miles, and from Point Arguello, 32 miles. Southward to Point Conception the outer edge of the lower platform, like that of the upper one, follows the general direction of the coast line. South of Point Conception, however, the coast makes an abrupt change from the general southeasterly direction which it has been following for more than 500 miles, to a general direction, between Point Conception and San Diego, of east southeast; while the outer edge of the lower platform still keeps the same general direction as before, to a point about opposite the southern boundary of the state, where it, too, makes an abrupt change to an easterly direction. The result is a great curving embayment of the southern California coast line, about 250 miles in length, facing a broad submarine shelf (the lower platform), which has a maximum width in this region of about 120 miles. From the outer edge of this platform the descent is comparatively rapid to oceanic depths of 10,000 to 12,000 feet or more.

The depth of the ocean floor, off the Pacific Coast of the United States, varies considerably, showing a gradual decrease as we go northward. Opposite San Diego the depths reached off the coastal platform are from 12,000 to 15,000 feet; while opposite the mouth of the Columbia River the depth is only 9,200 feet at a distance of about 225 miles from the shore.

* All distances are given in *statute* miles, unless otherwise indicated.

The descent from the upper or lower platform to the ocean floor seems abrupt, on the map, and is suggestive of a great fault or flexure, dying out to the northward. Estimated in degrees, the slope is seen to be very gradual, the maximum being about seven degrees, found at several points off the California coast. In general the slope is considerably less than that, the average probably lying between three and four degrees.

The broad lower shelf opposite the embayment of the southern California coast appears to have been an area of great orogenic disturbance, giving rise to many irregularities in the surface form of the shelf. Locally, many parts of this great area are broad and platform-like, but as a whole it is quite uneven, with many depressions and elevations. The most pronounced of the latter are, of course, the islands and banks.

The marked depressions in this area, as given on the map, are as follows: To the north of San Nicolas Island, at a distance of about twenty miles, there is a depression with a depth of more than 5,400 feet; between San Nicolas and San Clemente Islands, a broad depression with a depth of about 5,700 feet; southeasterly from San Clemente a depression with a depth of more than 6,000 feet; northwesterly from San Nicolas, and near the outer edge of the platform, is a long but not pronounced depression with a depth of about 4,000 feet.

On the other hand, there is apparently a broad submarine ridge between San Nicolas and Santa Rosa Islands, with a maximum depth of water of some 1,200 feet. About thirty-five miles southwest of San Nicolas there is a shoaling of the water, to a depth of about 2,400 feet. About thirty-five miles west of the coast of San Diego County is a submarine elevation of considerable size, with a depth of water of from 1,200 to 1,800 feet. Southwesterly from San Clemente Island, and at a distance of about twenty-five miles, another shoaling of the water is indicated by a depth of only 1,944 feet. Cortes and Tanner Banks, and Osborn Bank to the south of Santa Barbara Island, have been already mentioned. Southwest of Cortes Bank, and evidently near the outer edge of the lower platform, we find a depth of only 1,770 feet.

Considering the upper platform in more detail, for the southern

portion of the California coast, the description given by the writer* for the submarine features of Santa Catalina Island would serve as a general description for this entire region. (See fig. 2.) The slope

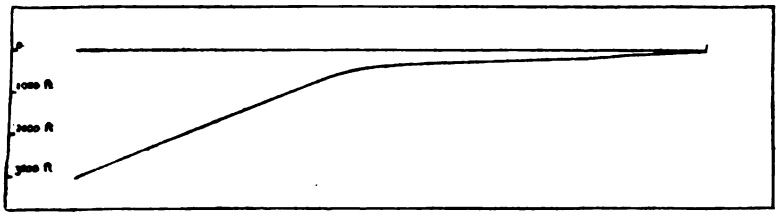

FIGURE 2.—Submarine profile, southern side of Santa Catalina Island.

of the platform is generally least between the depths of 200 and 400 feet. Above 100 or 200 feet the slope is in general a little greater, to the present coast line. Below 300 or 400 feet the slope increases rapidly, being usually more or less uniform, below 600 feet, till the lower platform is reached. These features are not equally well developed at all points, nor in quite the same way. At some points the gentlest grade is between the 100- and 300-foot submarine contours; occasionally the grade is more or less uniform from the shore to a depth of 300 or 400 feet, and exceptionally the rise from the lower platform to the shore line is not marked by any pronounced terrace.

The upper submarine platform is believed by the writer to be due to marine action,—in part deposition, though largely abrasion. The conclusion is based on the following reasons: (1) It borders continent and islands alike, and its general characteristics are the same wherever found. Since it follows the general irregularities of the continental shore line and encircles all the islands, it can not be due to crustal deformation. (2) It is widest in the regions of greatest deposition (e. g., to the northwest and southeast of San Pedro Hill) and of most active cliff-cutting; the latter cases corresponding, in general, to the best development of the elevated terraces. These points of greatest development of both terraces and submarine platform are the salients and the gentler slopes in general. It may be said that the greater breadth of the submarine

* The Geology of Santa Catalina Island, pp. 65, 66.

platform on gentle slopes may be accounted for by considering the submarine slope as simply a continuation of the subaerial slope, since a low grade would normally give a greater distance from the shore line to a given contour than would a higher grade. But it must be remembered that this platform has in no case (except where deposition appears to be the controlling factor in its formation) the character of a mere continuation of the subaerial slope; it has everywhere the bench or terrace form. This taken in connection with the fact (which will be shown later) that wave cutting is greater on gentle slopes than on steep ones (as the terraces bear witness), and the close correspondence of the platform's development with that of the terraces, would go far to establish the origin of the platform through wave action.

The platform* as developed about San Pedro Hill is widest off the western and southeastern salients, above which are found the broadest and best developed elevated terraces. In the case of Santa Catalina Island, the platform is wider on the side facing the open ocean than on the landward side (the average width on the landward side being a little over a mile, on the ocean side, nearly two miles). It is, on the whole, wider in the igneous rocks than in the harder quartzites; and it is widest of all on the salients. At the northwestern end of the island the platform has a width of two and a half miles; at the southeastern end, a width of about four miles; and at the salient south of the Little Harbor region, a width of somewhat more than four miles.

Along the southwestern face of San Clemente Island, the platform has an average width of three miles, while on the northeastern side of the island the average width is about half a mile. The best development of the platform on this side is found near the northern end of the island, where folding in place of faulting has given rise to somewhat gentler slopes. Along that part of the northeastern coast where the fault scarp is most abrupt, the submarine platform is inconspicuous. It reaches its greatest width, for this island, off the salients at either extremity of the island, the maximum being

*In what follows the width of the submarine platform is estimated from the shore line to the 600-foot submarine contour, since the position of this contour varies but little from that of the outer edge of the platform.

off China Point. Thus the development about San Clemente corresponds with that of the elevated terraces, since they are best developed on the southwestern facing, and but little developed on the northeastern side of the island. From a map of San Clemente on which the principal elevated shore lines have been plotted, it is readily seen that during the various stages in the elevation of the island the greatest width of the submarine platform has always been, as now, at the extremities of the island.

The platform is broadest on the landward side of San Nicolas, where the slopes are gentle, and narrowest on the abrupt, ocean side, where it averages between a mile and a half and two miles in width. It reaches its maximum width off the salients at either end of the island, being about fifteen miles wide at the end facing the ocean, though considerably narrower than this off the landward end. The submarine platform is wider about San Nicolas than about any of the other islands. This is to be accounted for in part by the greater exposure to wave action, and in part by the softness of the rocks of which the island is composed.

The average width of the platform about Santa Barbara Island is between two and three miles. Its greatest development is on the east and west, on the slopes away from the main axis, where the cliffs are lowest. The maximum width is on the west, facing the open ocean.

In the case of all the islands of the northern group, the average distance of the 600-foot contour from the shore is greater on the north than on the south. The slopes of San Miguel Island are most abrupt on the south. The submarine platform reaches a maximum width of some thirteen miles to the northwest of this island; while it is narrowest to the southwest of the western end of the island, having a minimum width here of about three miles.

The distance to the 600-foot contour on the north of Santa Rosa Island ranges from about five to about eight miles. The platform is narrowest on the southwest, where the range is from two and a half to five miles. The maximum width is to the southeast, where it is probably due to structural conditions. If Santa Rosa and San Miguel Islands together constitute a faulted crust block, as already suggested, with the fault scarp on the southwest,

the maximum width of the submarine platform is at either end of the block, while the minimum width is along the fault scarp. The 600-foot contour runs in a northwesterly and southeasterly direction.

As shown by the soundings in figure 1 and Plate 5, Cortes, Tanner, and Osborn banks exhibit characters identical with those of the upper submarine platform. They are more or less platform-like in character, and at an average depth corresponding to that of the submarine platform, and the descent beyond the 600-foot contour is generally rapid. There can be little doubt, therefore, that these banks were islands, only a short time ago, geologically speaking, and that they have been completely truncated by wave action during the most recent stages of marine abrasion.

If the coastal platform is wave-cut and -built, as the writer believes and as the above details would go to show, then the following conclusions with regard to the later history of the coast may be drawn from its general character. The broad surface with gentle gradient between the 200- and 400-foot submarine contours would indicate a considerable period during which the land stood near one level. This evidence is strengthened by the fact that this interval is comparatively wide even where the rocks are hard and the cliffs high and abrupt; for, as will be shown later, cutting along such a coast line is comparatively very slow. The generally steeper slope between the 200-foot contour and the shore line would indicate a much shorter period during which the land was sinking. Whether or not the depression is now in progress can not be stated. These conclusions are in accordance with the evidence furnished by drowned valleys in the case of those islands whose topography admits of such features.

The exceptional width of the submarine platform as compared with that of the elevated terraces may be accounted for in part by a prolonged period of wave action at or near one level, as already indicated; in part, also, by the fact that the last formed of a series of terraces is apt to be broader than those previously formed, at higher levels, because each succeeding terrace in cutting back its cliff tends to cut away and obliterate the platform of the terrace next above.

It may be objected that such submarine features as are here described might normally be developed by wave action and coastal currents along any coast line, with sea level nearly stationary for a considerable period. It is to be noted, however, that where cliff cutting is taking place the general features as described are best developed; and where deposition, not cutting, is in progress, as in the embayments, and along those parts of the main coast where wave- and current-built features are forming, the submarine features depart most widely from the general type. Where shore drift is furnished in comparative abundance, the off-shore depths may be built up rapidly to those normal to the present sea-level Where drift is rapidly removed by waves and currents from a region of active cutting, and in particular along the rugged coasts where cutting is slow and the amount of shore drift inconsiderable, the features in general conform most closely to the description of the whole. It is for these reasons, in addition to the fact of the drowning of the lower parts of the broader valleys, along parts of the island coasts, that the submarine features are believed to indicate a comparatively recent coastal depression.

Well-developed beaches are uncommon on the California coast. We should expect them to be more numerous, considering the width of the submarine platform, if the land had stood at or near the same level throughout the time of its formation. If, however, a recent depression of the coast is postulated, the scarcity of beaches is easily accounted for.

Since the general characteristics of the upper platform are similar about all the islands considered here, and along the main coast of this part of the state, it is concluded that the latest recorded movements have been uniform for all of this part of the California coast.

Notching the upper platform and its outer escarpment, along the Pacific Coast between San Diego and the Columbia River, are a number of submarine valleys, which have been described in considerable detail by Professor Davidson.* Some nine of those de-

*The Submerged Valleys of the Coast of California, U. S. A., and of Lower California, Mexico. Proc. Calif. Acad. Sci., Third Series, Geol. Vol. I, No. 2, 1897.

scribed and figured by him occur within the area under consideration.

In explanation of the origin of these submarine valleys on the California coast, two views have been put forward by Pacific Coast geologists—one that they are structural in origin, and the other that they are submerged stream valleys. Neither of these views is wholly satisfactory, especially in accounting for those valleys which head close to the shore line, as the majority of them do. While there can be little doubt that some of the valleys are due to crustal deformation, it would seem that the majority are to be accounted for in some other way—though it by no means follows that this way is the submergence of stream valleys. Further, each valley must be considered by itself, since the explanation for any one is not necessarily the explanation for all. Probably a final and satisfactory explanation can be given, if at all, only after a careful study of the geology in the region about each one of the submarine valleys.

The northern group of islands is separated from the mainland by the Santa Barbara Channel, the deepest part of which, forming a basin-like depression, lies to the north of Santa Rosa Island, and has a maximum depth of about 2,200 feet. To the west of that depression a broad submarine ridge extends from San Miguel Island northward toward Point Conception, the lowest part being at a depth of about 1,450 feet. At the eastern end of the channel, between Anacapa Island and San Buenaventura on the mainland, and connecting the upper coastal platform with that of the islands, though at a somewhat lower level, is another short submarine ridge, whose lowest part, about one-third of the distance between the islands and the mainland, shows a depth of water of only 700 feet. As the passages between the islands themselves are in no case of greater depth than 200 feet, an elevation of the coast of a little more than 700 feet would connect the entire group with the mainland.

The submarine ridges across either end of the Santa Barbara Channel have doubtless been formed through deposition due to conflicting currents at these points. If caused in this way, both ridges (especially the eastern one) are now and must have been in

the past variable structures, changing with the strength and character of the currents in and about the channel, and with the amount of detritus transported by them. The eastern end of the channel is opposite the mouth of the Santa Clara Valley of the South. During the recent depression of the coast the stream of this valley would have been engaged rather in building up its grade than in corrading its channel. During the post-Pliocene elevation, however, the conditions must have been, in general, different, and during at least a part of that time the stream has been engaged in re-excavating its valley, partially filled during the Pliocene depression. At such times it must have furnished considerable detritus to the neighboring coastal currents. It is not at all improbable, therefore, that at some time (or times) during the later stages of the coastal elevation, when drift was abundant or other conditions were especially favorable, the eastern ridge was built to the very surface of the ocean, so as to make a land connection with, at least, the eastern islands of the group, and afterward broken down by waves and currents during later movements of the land.

The broad embayment of the southern part of the California coast had, during Pliocene and a part, at least, of post-Pliocene times, a much greater extent than at present, since it included a broad area of comparatively shallow water, extending from the present coast line inland to the eastward of Los Angeles. Along shore it extended from just north of Santa Monica to Newport Bay. This area, which will be spoken of as the Los Angeles embayment, is now a low plain, bordered by mountains on all sides except the seaward facing; and near the center of its coastal border stands the isolated mass of San Pedro Hill.

Coastal Topography.—The comparative value of the various factors concerned in the evolution of coastal topography can best be learned from the study of actual occurrences where one or more of these factors, through unusual development, become of prime importance in the formation of certain coastal features, or where, through the variation of some other factor or factors, the factor under consideration becomes of relatively greater importance. Such has been made the main basis for the following conclusions. Owing to the variety of conditions presented, the field under discussion is an

unusually favorable one for the study of certain shore features, particularly terraces. The conclusions drawn from the study of the phenomena in this region have been verified, as far as possible, by comparison with other regions of the United States where similar features are found. Gilbert's classic work* has, of course, furnished most of the fundamental principles involved.

The principle which it is desired to emphasize throughout this section of the paper is the dependence of the development of shore features on the character of the subaerial coastal topography.

If a given region long subjected to the forces of subaerial erosion is depressed, the off-shore slopes will necessarily be those characteristic of subaerial erosion. Along the immediate coast line the subaerial slopes, before depression, will of course have been modified to a greater or less extent through marine action in the process of forming sea cliffs, so that they may present a considerably steeper angle than that due to subaerial erosion alone. In any case, however, the erosion slopes will be gentler in the less resistant rocks, and the off-shore slopes after submergence will therefore be less, than in the case of the more resistant rocks. The more resistant the rocks to erosion, the greater will be the angle of slope. The least submarine slope will be given by areas of sedimentation, as the floors of broad valleys carried beneath sea level.

If, on the other hand, after a long period of comparative quiescence, a moderate elevation occurs, the immediate on- and off-shore slopes will be those characteristic of the subaqueous platform produced by marine abrasion, and therefore of a very low angle. This is the present condition on the Atlantic Coast, while the former condition prevails on the California coast. At the close of the Miocene the California coast was elevated more than at present, in all probability some 3,000 feet. After a prolonged period of erosion it was submerged, and in the rise that followed, the post-Miocene elevation of the land was only in part recovered. It is therefore assumed that the average on- and off-shore slopes of the California coast are in general those characteristic of subaerial erosion, modified near the present sea-level by a prolonged period of wave action which has formed the submarine platform, or "continental shelf,"

*U. S. Geol. Surv., Monograph I, 1890. Lake Bonneville.

already described. Thus, while the platform itself is due to marine abrasion, its outer scarp presents slopes characteristic of subaerial erosion, modified to a greater or less extent by deposition through marine action. This is believed to have been the condition in general, also, throughout the post-Pliocene elevation of the coast; that is, that the off-shore slopes, as successive elevations of the land occurred, were largely those characteristic of subaerial degradation, and therefore greater in the more resistant than in the less resistant rocks.

Where young subaerial topography is found along a coast line, gentle slopes and slightly dissected surfaces are ordinarily presented, whether the rocks are hard or soft. Exceptionally, such forms may present high, abrupt slopes to wave action, as in the case of a fault scarp facing the ocean. Old subaerial forms are also characterized by gentle slopes and moderate contrasts. Such forms along a coast line present a variable, though always moderate, angle of slope to wave action.

Mature subaerial forms present the greatest contrasts, such topography, in rocks of varying degrees of resistance, being generally rugged, as a whole. Where the rocks are hard it will be characterized by a generally bold shore line, with high, precipitous cliffs, though softer rocks will give gentler slopes and lower cliffs. If gentle subaerial slopes with little dissection (and therefore young) are found in the more resistant rocks along such a coast, they can be ascribed only to accident (*e. g.*, faulting). Along the California coastal region, the harder rocks present normally steep and well-dissected subaerial slopes, while the softer ones show slopes of very moderate angle, and usually much less dissected. The gentle slopes found on the slightly dissected ocean facing of San Clemente Island, in rather resistant volcanics, are therefore abnormal and accidental, being due to faulting.

With only slight original elevation above sea level, mature forms in rocks of any degree of resistance would differ to a greater or less extent from forms developed in the same rocks with greater original elevation. The matured forms considered in this paper are those resulting from a considerable original elevation, as exemplified in the Coast Ranges of California.

As a general rule, the gentler the slopes, in a given region, the less resistant the rocks, the gentlest slopes being found in incoherent, readily eroded material. The exceptions to this are as indicated above, on some very young surfaces. Such very gentle slopes are readily cut by the waves, and usually furnish abundant shore drift. The least shore drift is furnished by abrupt slopes in resistant rocks, such as form a considerable proportion of the California coast.

As regards the age of coastal topography, we may have young, mature, or old coast lines characteristic of any given age of the subaerial topography; and the coastal forms of a given age will differ with the age and character of the subaerial forms on which they are imposed. For example, a young coast line in a region of generally young topography will differ in character from an equally young coast line in a generally mature region. Also, since the characteristics of inland topography of any given age differ according to the resistance to erosion of the rocks in which they are cut, the original amount of elevation of the surface, etc., the coastal forms of a given age will vary to correspond with such differences.

Development of Wave-Cut Terraces.—The laws governing the development of a series of terraces on a rising coast must be deduced from a study of the single terrace and the single shore line. Cliff erosion, with the consequent development of a subaqueous platform, the principal shore feature with which we have here to deal, is dependent on the action of the waves, concerned principally in erosion, and on the character of the coastal currents, concerned mainly in the transportation of the eroded material.

The strength of wave action in cliff erosion is dependent on the direction of the prevailing winds, the distance from which the waves come, the direction in which they approach the shore, and on the character and slope of the bottom, as well as on the amount and character of the detritus along the immediate shore line. The stronger the waves the more active will be the erosion; and the swifter the shore currents the more rapid the transportation of the débris, too much of which acts only as a clog to further cliff cutting.

Wave action is greatest, other things being equal, where there

is a moderate off-shore slope. Too low an angle of slope, however, will act as a complete, though temporary, check to cliff cutting, the force of the waves being dissipated over a broad and shallow zone, which must be worn down before cliff cutting can take place. Wherever continuous cliff cutting is taking place, the off-shore slopes must be worn down at the same time, in order that the waves may continue to do effective work on the cliffs.

Where the original slope of the bottom is at a high angle, the energy of the waves at first must be devoted to the task of building up the off-shore slopes, before active cliff cutting can take place. Abundant detritus (however derived) is essential to this process. Where such detritus is comparatively scanty (as is the case along the California coast in general), the effective work of the waves in cliff cutting, on a steep slope, would be, of course, very greatly delayed. The conditions might be such, in some cases, that while a comparatively broad terrace would develop on a low slope, no terrace at all would be formed in the same time on a steep slope.

It has already been shown that, accidents excepted, the general on- and off-shore slopes are roughly the same, at the outset of terrace development at any given level.

With low on-shore angle of slope the sea cliffs are necessarily lower than where the subaerial angle is high—the angle being, as stated, normally dependent on the resistance of the rocks, in regions of mature topography. With waves of equal strength, cliff cutting, even after the necessary conditions are attained (see above), will be slower on the high than on the low cliff, not only on account of the greater hardness of the rocks normally forming such slopes, but also because, with the high cliff, more material must be cut away and transported for every horizontal foot of cutting; and since, on the whole, erosion can not exceed the removal of the material cut, the lower the cliffs the greater the advantage in this respect. As a natural result of slower erosion, terraces developed on a steep slope will be narrower than those on a gentler slope, other things being equal. High cliffs with abrupt off-shore slopes, even in the case of soft rocks (an exceptional condition in a region of mature topography), will be cut back very slowly, as would follow from the statements already made.

On a rising coast, where the subaerial and submarine slopes are at a high angle, and the cliffs correspondingly high, the comparatively narrow terraces formed are more rapidly obliterated through marine abrasion, after uplift, than in the case of a low angle of subaerial and submarine slope, and correspondingly low cliffs, with the resulting broader platforms, provided other factors are the same in both instances. This may be illustrated by the following example. Given two cliffs such that the ratio of the volumes of the material cut in the two cases, for every horizontal foot cut back, along a given length of coast line, is as one to five. This ratio will be given by slopes with a rise of ten feet and fifty feet, respectively, in every hundred feet—corresponding to angles of 5° 42′ 38″ and 26° 33′ 54″ (angles A′ C′ D′ and ACD in figure 3).

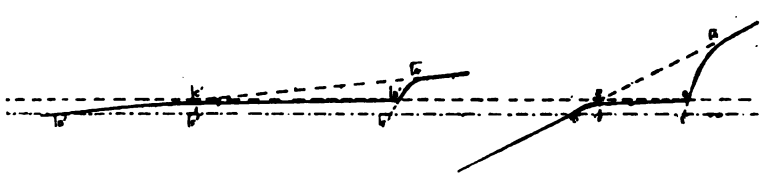

FIGURE 3.

To simplify the conditions of the problem, the cutting may be assumed to be in homogeneous rocks, and all other factors except slope (such as character of rocks, fetch of the waves, strength and character of the off-shore currents, etc.) may be considered as the same in the two cases. Further, we may neglect the fact that the sea cliffs are not perpendicular, and also the amount of coastal detritus deposited on the submarine slopes beyond the platform cut by the waves, since neither of these factors (uncertain in any case) would materially affect the general result.

Since, at the outset, with the sea-level C′B′—CB, the submarine slope CD is the steeper, the waves will be longer in making an active start in cliff cutting than on the slope A′C′D′. Although this difference is an important one, it may be set aside for the present, as it will be taken into account later. Considering, then, that in a prolonged period of wave cutting, equal volumes are removed in a given time in the two cases, it follows that when a distance C′B′ of 1,500 feet has been cut in the gentler slope, a

distance CB of, roughly, 675 feet will have been cut in the other slope.

If, at this point, an elevation of 100 feet occurs (indicated by the new sea level D'E'—DE), the shore line, for the gentler slope, will be shifted from B' to D', a horizontal distance of 2,500 feet (B'C' = 1,500 feet, and D'F' = 1,000 feet, for the angle assumed). The shore line of the steeper slope will be transferred from B to D, a horizontal distance of about 875 feet (CB = about 675 feet, DF = 200 feet, for the angle assumed).

As before, the waves will be somewhat longer in making a start at D than at D', on account of the steeper off-shore slope, but this difference in the beginning of the *destruction* of the two terraces, C'B' and CB, will be practically offset by the corresponding difference at the beginning of their *construction*, when the sea made its first attack at C' and C.

Since DF is smaller than D'F' (the ratio being one to five in the example under consideration), and since the altitudes F'C' and FC are approximately the same, the volume to be removed in cutting back from D to F is less than that to be removed in cutting back from D' to F' (roughly one-fifth, in the present case); so that the point F will have been reached by the waves before the point F' has been reached. After the waves have cut back in both cases to the terrace platforms, C'B' and CB, the further cutting will be at approximately the same rate for both, since the cliffs now have equal altitudes (about 100 feet above sea-level),* and other conditions are the same in the two cases, except that there will be a greater width of submarine platform to be worn down in connection with the cliff cutting in the obliteration of the terrace formed on the gentler slope than in the case of the steeper slope. This will offset the corresponding difference in the formation of the terraces.

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*These first platforms were not level from front to rear, but had a seaward inclination, owing to the abrasion of the platform surface off-shore; so that after elevation the height of the cliffs is less than 100 feet above sea-level, on the average. This is offset, however, by the fact that in the cutting at the second level the second platform must be worn down by a corresponding amount.

Since, then, the waves will have cut back to F before they have reached F′, and since the cutting away of the terraces themselves is at approximately equal rates, and since, further, the terrace CB is much narrower than the terrace C′B′ (the ratio of the widths being about 7:15), it follows that the waves will have cut back to the first sea cliff, AB, long before the corresponding point in the other case will have been reached. Thus we conclude that not only are narrower terraces formed where the angle of slope is high, but they are sooner destroyed by wave action, after elevation.

The angles assumed in this illustration are such as are not at all uncommon on the coastal slopes of California, in moderately hard and soft rocks, respectively.

As a rule such differences of slope as are shown in these figures would be accompanied by a difference in the resistance of the rocks to erosion. But even if the rocks forming the slope A′C′D′ were much less resistant than those forming the slope ACD, the conclusions just reached would not be changed. For, regardless of rock character, if the distance C′B′, with low angle of slope and low cliffs, is equivalent to the distance CB, with higher angle of slope and higher cliffs, then with cliffs of equal height in both cases, CD will have been cut back to BE long before C′D′ will have been cut back to B′E′. Or, looked at in another way, while a terrace formed on gentle slopes in softer rocks will be more readily obliterated on elevation than one formed on the same slopes in harder rocks, this will be largely offset by the more rapid cutting in the formation of the terrace, which will give a comparatively greater width of platform to begin with.

The chief factor in wave cutting, as illustrated above, is the amount of material removed for every foot cut. This depends on the height of the cliff, and this, in turn, depends, normally, on the angle of slope. Hence slope is spoken of as the essential factor, but it must be remembered that it is considered in connection with cliff height.

An example of the extent to which the elevated terraces have been obliterated by those formed at lower levels may be taken from San Clemente Island, where the 80-foot terrace now ranges from nothing to a maximum width of about one-third of a mile.

Its outlines are still sharp and clear, but it is only a remnant of its original form; for its width before it had been cut into by the succeeding lower terraces could not have been greatly less than that of the present submarine terrace, so that we may assume it to have been at least two miles. If, then, the best developed and preserved of the elevated terraces are at the present time comparatively mere remnants, as on the lower slopes of the ocean facing of San Pedro Hill and San Clemente Island, where the angle of slope was low (5° to 7°), and the conditions in general more than usually favorable to terrace development and preservation, we could scarcely expect to find pronounced elevated terraces, or in most cases even traces of terracing, where the original angle of slope was high (25° or more). The present period of wave cutting has been a long one, to judge from the development of the submarine platform, so that there has been ample opportunity for the obliteration through wave action of the comparatively narrow terraces which would be formed on the rugged coast line. This submarine terrace is pronounced off Santa Catalina Island, and in its development cliffs have been produced running up to 1,000 feet or more in height. In any case, it is certain that, whatever height the present actual sea-cliff attains, on that shore no terraces can be found below its upper edge.

Other things being equal, cliff cutting is more rapid on the side from which the greatest waves come. That this factor, however, (beyond a certain minimum fetch of the waves which must be assumed in order that they may develop in sufficient size for active cutting) is not so important as the slope of the surface on which the cutting takes place, is seen on San Nicolas Island. Here the side from which the greatest waves come exhibits only a narrow submarine terrace, and no elevated terraces have been recorded on this side of the island; while on the northern or landward side this submarine terrace is of remarkable development (though here best developed where there is the greatest exposure to the waves from the open ocean).

In the writer's opinion, whatever movements may have taken place since the first elevation of San Clemente and San Nicolas, these have been insufficient to prevent the possibility of terracing on

the steep faces of these islands. At the present sea-level a terrace of greater or less extent has been developed (see fig. 4) on the

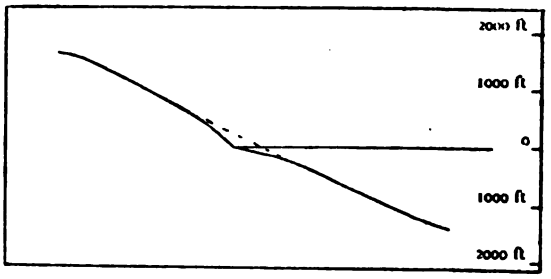

FIGURE 4.—Subaerial and submarine slope on the northern side of San Clemente Island, where the submarine platform is least developed.

steeper sides of both islands. Further, in the case of San Clemente, elevated terraces are found on the steeper side, toward the northwestern end of the island, where the slopes are somewhat gentler.

Other things being equal, cliff erosion is more rapid in soft than in hard rocks. The more resistant character of the harder rocks will be somewhat offset by the greater hardness of the cutting tools furnished by its disintegration. But the beach material at any given point may be composed to a greater or less extent of drift from other parts of the coast, in addition to the material of its own cliff. This would render the influence of the difference in cutting tools more or less uncertain. The differences resulting from difference in the character of the rocks are seen in the cases of San Clemente and San Nicolas, where the conditions are somewhat similar, except that the gentle slope of San Nicolas faces the land, while that of San Clemente faces the ocean. The submarine platform of San Clemente, though broad, is much less so than that of San Nicolas.

That a moderate slope, with its consequent low cliffs, and therefore more rapid cutting, is of more importance (up to a certain limit) than the character of the material eroded, is seen by comparing Santa Catalina and San Clemente Islands, both of which are composed largely of hard rocks. San Clemente, with its gentle slope on the southern side, is terraced in a remarkable degree, while Santa Catalina, with its high, sheer cliffs, shows only one pro-

nounced terrace, and that submarine. Further, in the case of San Nicolas, no pronounced terraces have been developed on the steep southern face, notwithstanding the softness of its rocks.

Thus marine abrasion in the softer rocks, where the subaerial topography is generally mature, is more rapid, not only on account of the greater resistance of the harder rocks, but also on account of the gentler slopes which characterize the softer areas. Further, given a submergence of both harder and softer areas, the terraces formed on the latter are more nearly continuous (or sooner become so), and therefore more evident to the eye, than those formed on the surfaces of the harder rocks, since the general subaerial dissection is less pronounced in the softer than in the harder areas. If a deeply dissected area of resistant rocks, characterized by steep slopes and V-shaped canyons, is submerged, the terracing will occur at first mainly along the submerged divides, which now form the salients of the coast line. This notching of the crests can never form so marked a feature as continuous terracing even of the same development in other respects, and where such broken terraces are worn down by erosion their recognition is sometimes very difficult. This will account, in part at least, for the doubtful character of the notching near the southeastern end of Santa Catalina (see page 190). If, in such a case as that just referred to, the ocean remained for a sufficient length of time at one level, the salients would, of course, be cut back, so as to give a more or less continuous terrace.

Cutting is most rapid, other things being equal, where the material composing the sea cliffs is most nearly in the condition for transportation, or is most readily brought into that condition, as in the case of a friable sandstone, or a loose-textured rock of any sort.

Rapid removal of the material cut away by wave action is essential to further rapid and continuous cutting, the most favorable condition being that in which the material is disposed of by currents as rapidly as it is furnished by the waves. It would therefore follow that wherever rapid cutting is taking place, there is also rapid removal of the eroded material. The finer the particles transported by littoral or other currents, or the more powerful the currents, other things being equal, the more widespread will be the

distribution and deposition of the eroded material, and therefore the less the deposition immediately off shore or along shore. It may be noted here that, in general, the greater the amount of drift passing any given point along a coast line and derived from other parts of the coast, the less rapid will be the cutting at that point; since the drift thus transported must be disposed of by waves and currents, in addition to that derived from the immediately adjacent shore line.

A terrace formed during a slow depression will be broader, other things being equal, than one formed during a slow elevation. For, during depression the off-shore depths are slowly increased as the cliffs recede under the attack of the waves, thus avoiding, to a greater or less extent, the continuous submarine erosion otherwise necessary to continuous cliff cutting. On the other hand, elevation only increases the difficulty to be overcome, necessitating more than the normal erosion to keep the off-shore depths sufficiently great for active cliff cutting. It is possible that the width of the present submarine terrace is due in part to a very slow depression of the coast during the earlier stages of its development.

From the comparative study made of wave-cut shore features, it appears that, of all the foregoing single factors concerned in the production of pronounced terracing, that of cliff height, normally dependent on slope, is the most important, provided the waves have the minimum fetch necessary for active cutting.

Preservation of Elevated Wave-Cut Terraces.—We have next to consider under what conditions terraces, after elevation, best resist the subaerial forces of destruction. If terraces are equally well developed in hard and soft rocks, on surfaces of moderate slope and not greatly dissected, they would be better preserved in the hard rock. For, in order to have equal development in the two cases, it would be necessary, in general, that the slope in the harder rocks should be at least as low as that in the softer; and, with equal slopes, general subaerial erosion (and consequently terrace obliteration) is more rapid in the soft than in the hard rocks. With equally abrupt cliffs at the rear of the terraces, those in the harder rocks would preserve their sharp outlines for a longer time, those in the soft rocks soon becoming softened and rounded in

their outlines. In comparing the terraces of San Clemente, San Pedro Hill, and San Nicolas, their present sharpness is seen to vary with the resistance to erosion of the rocks in which they have been cut. The best preserved and sharpest terraces are cut in the volcanics of San Clemente, while those cut in the sandstones of San Nicolas have been most modified through general subaerial erosion. The rounding of terrace forms may take place in part through the falling away of the upper portion of the cliff, with deposition of talus at the angle of cliff and terrace, and in part through stream erosion wearing away the upper portion of the cliff, and forming alluvial fans at its base.

Terraces are better preserved where they form continuous benches, on little dissected surfaces, than where they are discontinuous, forming merely a series of notches on the sharp ridges of a well-dissected surface (in hard rocks). In the latter case, erosion on the slopes of the ridges, by narrowing their crests, soon tends to obliterate the imperfect terraces. At the outset the dissected area is in a condition (as regards the preservation of the terraces) similar to that of the undissected area after a considerable period of subaerial erosion.

Where, along the coast line of well-dissected areas of hard rocks, with high angle of slope, the cutting has been sufficient to produce continuous terraces (which will be narrower, as has been shown, than those formed under similar conditions on gentler slopes), these terraces, on account of the more incisive cutting due to subaerial erosion in these resistant rocks, will soon become discontinuous, and therefore more readily obscured.

With cliffs of varying height or platforms of varying width, in a given rock, the higher the cliff or the broader the platform, the longer will the terraced character be evident. Where a narrow terrace with comparatively high cliffs at its rear is developed (in hard rocks), it may soon be buried by detritus from the cliff above, and its character thus be lost. Thus breadth of platform is seen to be more important than height of cliff to the preservation of terrace character.

All things considered, then, in a region of mature topography (accidents excepted), a rock of only a moderate degree of resist-

ance, with its accompanying moderate dissection and moderate angle of on- and off-shore slope, is best fitted for the development and preservation of wave-cut features.

Some of the best developed and preserved terraces along the California coast are in the Miocene shales,* which furnish the conditions just laid down.

The principles here stated are illustrated along the California coast generally, as well as on the islands which have been especially considered. Terraces are found well developed in the softer, little dissected rocks, where moderate slopes are presented to wave action. They are found little or not at all developed in the more rugged forms, with high angle of slope, characteristic of mature topography in hard rocks; and where developed, they are, in general, but imperfectly preserved. The difference in the character of the topography and evidence of terracing is not, therefore, a certain indication that the two forms have not been subjected to the same conditions, as regards both subaerial erosion and terracing. So that the more recent movements of the islands as a whole have not been the same, can not be predicated from the presence or absence of terraces, so long as the topographic forms are such as to warrant, on the principles already laid down, a terraced structure in one case, and a non-terraced, or but slightly terraced, condition in another. There are many miles of rugged, unterraced topography along the mainland coast of California, adjacent to forms yielding pronounced terraces.

The position of San Clemente Island, as regards terracing, is exceptional for the California coast, primarily because of the combination of hard rocks with low angle of slope. This combination, on a generally mature coast, could be due only to accident. Through faulting, a very slightly dissected surface of low angle of slope has been presented to wave action in the direction from which the greatest waves come. As we have thus a combination of the most important factors in both the development and preservation of terraces, the natural result is a remarkably well-developed and well-preserved series.

*See, Lawson, The Geomorphogeny of the Coast of Northern California, Bull. Dept. Geol., Univ. Calif., Vol. I, No. 8, 1894, p. 247.

Wave- and Current-Built Features.—The essential factors in the formation of *barriers*—aside from the necessary waves and current—are (1) abundance of drift, (2) gentle off-shore slopes, (3) nearly unbroken shore contour. (1) The chief of these three factors is an abundance of drift, of such size as to be readily transported by shore currents, the supply being continuous and greater in amount than may be readily disposed of off shore by wave and current action. This supply may come from neighboring sources, or it may come from a distance, transported to the point of deposition by shore currents. When so transported, a practically continuous road-bed, either beach, barrier, or embankment, from the point of supply to the point of deposit, is also necessary. This supply of drift may come from the shores through wave cutting, or it may be furnished by rivers, or it may come partly from both sources. In no case can the supply of drift come from the part of the shore where deposition is taking place; for active cutting and deposition can not occur at the same place at the same time. The barrier can persist only so long as the supply of drift is continuous. If this fails, through any cause, the barrier will be cut away, the submarine shelf worn down, and the shore line itself attacked.

(2) The steeper the subaqueous slopes the nearer the shore will any wave-built deposit form. For off-shore barriers, therefore, a very gentle off-shore slope is necessary, so that the wave attack may be at a distance from the shore. Such gentle slopes may be normal, or they may have been built up by abundant drift. Where such very gentle slopes occur they can be preserved only by an abundance of drift; for without this the subaqueous slope will be gradually worn down, and the waves will cut back shoreward.

(3) A nearly unbroken shore contour for considerable stretches is essential for the development of *extensive* barriers. Such a shore contour may be formed originally, as by the elevation of the submarine platform, or it may be developed by modification of an uneven shore line through the accumulation of shore drift, where this is abundant.

The conditions along the California coast appear to have been very unfavorable to the formation of barriers during the period in which the terraces were formed. The rocks along this coast do

not in general yield abundant drift. Extensive incoherent deposits along the main coast are not common, and there are very few streams bringing to the ocean any considerable supply of detritus. The material brought within reach of wave action is in general readily disposed of, so that active cliff cutting is now taking place at nearly all points of the California coast. The same has been true, apparently, during all the time that the terraces were forming. For, along the coast, in general, where the slopes are gentle, active cutting and not deposition is shown by the wave-cut terraces. Where the slopes are steeper and the coast more rugged, though no terracing or only imperfect terracing is found, the conditions must have been still more unfavorable to the formation of wave-built barriers, on account of the steeper on- and off-shore slopes, and the more resistant rocks, supplying a very limited amount of drift.

Where barriers have been well developed, and are associated with low landward slopes (as would normally be the case), these features, on elevation, may preserve their chief characteristics for a long time. When built of loose, incoherent material, the forms may be greatly altered by winds, unless soon covered with a protecting mat of vegetation. However, where barriers are not now being developed to any considerable extent, as along the California coast, and where the conditions have been extremely unfavorable to their extensive formation in the past, such fossil features can not be expected on elevated parts of the coast, especially where the topography is rugged, and the slopes nowhere approach the low angle necessary for their development.

In the formation of *bars* as distinguished from barriers, the first essential is an irregular shore line, for in order to have a bar there must first be an interval to be spanned. In order that a bar may form across any opening or embayment of the coast, the entrance must have a certain width proportioned to the size of the opening itself. If the entrance is narrow and the embayment large, the entrance will not be barred, on a seacoast, on account of the tidal scour. If the embayment is very broad and open, and the water sufficiently deep, the shore drift will follow the coast line, instead of crossing from point to point.

Given a suitable embayment to be barred, the most important factor, as in the case of the barrier, is an abundance of material, of a size for ready transportation by the shore currents. The conditions with regard to this factor are similar to those already given for the barrier.

The formation of the bar is further dependent on the character of the coastal currents, their direction and strength, in relation to each other and to the other factors concerned. With a strong littoral current, sufficient material for the formation of a bar (hook, spit, &c.) may be transported, when with a weaker current the material might be ground up by the waves and disposed of off shore.

The bar is essentially a current-built feature, while the barrier is essentially wave-built. We may have a structure built across a very shallow embayment, which, though functionally a bar, is genetically a barrier, being due to wave action in shoal water. Though these two forms of coastal deposit are typically different, there are all gradations between the two extremes, through different combinations of the essential conditions on which each depends.

A region of mature topographic forms in generally hard rocks, yielding narrow and comparatively steep-graded valleys, and steep on- and off-shore slopes, gives in general very unfavorable conditions for the formation of bars. Beaches for the transportation of material will not be numerous or continuous. Detritus will not be readily or rapidly formed, and most of what is furnished will be disposed of off shore. If such a region is depressed, bars may be thrown across the mouths of many of the narrow canyons or of the streams, forming lagoons. These will not be long-lived, being filled sooner or later with sediments brought down by the high-grade streams; or else the embayments may be destroyed through the rapid cutting back of the sea cliffs. Even on such a coast, however, there will probably be exceptions, and favorable conditions may be found here and there for the formation of comparatively extensive bars.

It is to be noted that, along a sea coast, a moderate depression, general or local, is usually a condition necessary to well-formed bars, and that during a general movement of elevation, even after a

prior depression, the conditions would tend to grow more and more unfavorable to the production of bars.

Since bars are usually formed at the mouths or in the lower stretches of the stream valleys, if these valleys are narrow and comparatively steep-graded, the bars will soon be removed by the erosion of the streams, on elevation, just as the deposits made by the streams themselves during depression are removed on elevation. As the valleys broaden and their grade decreases, the bars formed will tend to preserve their character for a longer time. As their destruction will be due largely to the cutting of the stream which occupies the valley, the length of time during which they will be preserved will depend on the corrasive power of the stream, and on the extent of its wandering to and fro over the valley floor.

The general conditions governing the formation and preservation of other wave- and current-built features (spits, hooks, &c.), are similar to those for the features already described, and need not be considered separately.

Along the California coast the present conditions are in general unfavorable to bar construction. Large embayments are not numerous, the majority of the drainage lines reaching the ocean being minor ones. Most of the larger openings are too wide and the water of too great depth for the bay to be spanned by a bar; wave- or current-built features may, however, be found in such bays, along the curving shore line, partially or completely closing the mouth of some stream emptying into the bay. San Francisco Bay has its entrance kept open by the powerful tidal currents flowing through the Golden Gate. In a few instances where the circumstances have been favorable well-developed bars have formed, as, for example, at Humboldt Bay and San Diego Bay. Most of the minor valleys have probably not been flooded; but where bays have been formed at their mouths they have in most cases been destroyed, either by rapid cutting back of the cliffs, or by filling in with the deposits of the stream. Some of the larger and more open of these minor valleys are now drowned, without being barred; while a comparatively small number have bars formed at their mouths. Similar conditions to these for the minor valleys are found among the rugged islands off the coast, bars being uncom-

mon features, notwithstanding the fact that some of the canyons are drowned at their mouths. Wherever bars are formed across the mouths of the minor drainage lines, they are in such positions that they might readily be destroyed on elevation.

The Los Angeles embayment forms a marked exception to the rest of the California coast. During post-Pliocene times this was, at certain stages, a very shallow and extensive bay, with gentle off-shore slopes, furnishing especially favorable conditions for the formation of wave- and current-built features. Further, owing to the width of this great embayment, and the gentle slopes of its floor, the conditions since elevation are favorable to the preservation of any such features.

On the Redondo and adjacent sheets of the Topographic Atlas of the U. S. Geological Survey are seen what appear to be two extensive wave- or current-built embankments or series of embankments, within the Los Angeles embayment. One of these extends northward, along and near the coast, from the northern slopes of San Pedro Hill, for a distance of about eleven miles, when it turns to the east, running inland for about four miles, to join an elevated isolated mass southwest of Los Angeles. The structure is not simple, but consists of two distinct, parallel ridges, broad, flat-topped and mesa-like, separated by a series of slight depressions. Of these two ridges, the one nearer the coast has an average altitude of 150 to 175 feet, while the average altitude of the other is about 125 feet. The average width of the entire structure is about two miles.

The other structure referred to lies at a distance from the coast for the greater part of its length. It begins at the north about five miles east of Santa Monica, and extends, as a low and broad ridge, southeasterly across the entire Los Angeles embayment, a distance of about forty miles. In its course and near its northern end (southwest of Los Angeles) lies the isolated elevation already referred to, the height of which is 517 feet. From this hill the ridge runs to the present shore at Anaheim Landing, about ten miles east of San Pedro Hill. From this point its course is along the shore to Newport Bay, at the southern end of the Los Angeles embayment. The ridge has an average width at its base of,

roughly, two miles, and an average elevation of about 200 feet. It is generally flat-topped, and at various points it is modified by terraces at different levels. It has also been cut through at a number of points by the present streams of this region, whereas the first structure described has been cut through at only one point, at the base of the isolated hill already referred to. While it is probable that this last-described structure, as a whole, is a former wave- or current-built embankment, it is possible that, in addition to the hill just mentioned, there are other outstanding remnants along its length, for example, Los Cerritos, to the east of San Pedro Hill.

So far as known to the writer, no elevated wave- or current-built features occur along the rugged parts of the coast, but those parts of the mainland showing no elevated coastal features whatsoever are frequently adjacent to areas presenting well-defined terraces or other coastal forms. This, taken in connection with the evidence afforded by the present coast line, in this respect, leads to the conclusion that the absence of any elevated coastal features, built as well as cut, in areas of rugged topographic forms, is not in itself an indication of a different history from that of a neighboring region where such features are found.

Drowned Valleys.—If a stream valley is flooded on depression, the amount of the flooding and size of the embayment formed are dependent on (1) the amount of the depression, (2) the width of the valley, (3) the grade of the valley near its mouth; the gentler the grade the greater will be the amount of flooding. The length of time during which a flooded valley remains in that condition depends on (1) the rate of deposition of detritus brought into the embayment by streams or through marine action, as related to the factors above. The smaller the embayment formed, and the more abundant the detritus, the sooner will it be filled. Drowned valleys may be barred at their mouths, forming lagoons which can not always be distinguished from lagoons resulting from a heaping up of shore drift at the mouths of streams which have not been depressed. For although the lagoon formed by depression would have had its bottom originally below sea-level, deposition would have led to a gradual shoaling of the water. The length of time during which a valley will remain flooded depends on (2) the rate of cliff recession,

as related to the other factors. The lower the cliffs, the softer the rocks, or the greater the exposure to wave action, other things being equal, the sooner the embayment will be destroyed.

Whether or not a stream valley will be flooded on depression is dependent on (1) the rate of depression as related to the size and grade of the valley, and to the rate of coastal deposition and cliff recession. If the rate of depression is sufficiently slow, the rate of coastal deposition and cliff recession may be such that, for a given coast line, no valleys will be drowned. The broader the valley and the gentler its grade near its mouth, the greater the amount of flooding, and hence the slower the rate of depression necessary to avoid flooding. Thus where valley width and grade vary along a coast line, a given rate of depression, irrespective of rate of cliff erosion and coastal deposition, might drown the valleys of greatest width and least grade, while the narrower and steeper valleys would not be flooded. The flooding of stream valleys on depression is dependent (2) on amount of depression. Where the mouths of the streams are above sea-level prior to depression,—owing to rapid recession of the sea cliffs, or any other cause,—the depression may be insufficient to carry them below sea-level, and in that event there can, of course, be no valley flooding.

Broad valleys of low grade, so situated that cliff recession is slow and shore drift scanty, are most favorable to valley flooding on depression and to the continuance of the flooded condition. On the other hand, small and narrow valleys of comparatively high grade, opening on a shore line favorable to rapid cliff recession, or in a region of abundant drift, or where much detritus is furnished by the stream occupying the valley, furnish conditions unfavorable to valley flooding or its continuance. Where, then, along such unfavorable shore lines, no flooded valleys are found, it can not be asserted, in the absence of any positive evidence to that effect, that no depression has occurred.

None of the islands belonging to the group with simple topography give any positive and unmistakable evidence of depression, through valley flooding, since the conditions along their shore lines are unfavorable to that phenomenon. Their stream valleys, either on account of youth or of the softness of the rocks in which they

are carved, are small and comparatively shallow, for the most part merely notching the surface just above the shore line. These surfaces, further, have a gentle slope favorable to rapid cliff recession. On the steeper slopes of San Nicolas and San Clemente Islands the stream courses are short and of unusually high grade, and the slight development of their valleys gives conditions still more unfavorable to flooding. Anacapa and Santa Barbara Islands are similar to the islands with simple topography, as regards stream development. Their small size precludes any large streams, and the conditions are therefore unfavorable to valley flooding.

The conditions most favorable to valley flooding, among the islands, are found among those with rugged topography. Many of their valleys, as compared with those of the islands in general, are broad and deep, with moderate grade near their mouths. The rocks of these islands being comparatively resistant and their sea cliffs comparatively high, the conditions are also favorable to the continuance of the drowned valleys, especially where the exposure to wave action is least. All of these islands show drowned valleys, those of Santa Catalina being the largest and most pronounced, while those of Santa Rosa, as might be expected from the character of its topography, are the least evident.

Thus the evidence from valley flooding is positive on the more rugged islands, and favorable to a comparatively recent depression. Since the evidence on the other islands is merely negative, it can not be stated that they have not suffered recent depression. Judging, then, from the positive evidence of their submarine features,—identical in character with those about the more rugged islands,—it seems that the recent depression has been general for this part of the coast.

Historical Sketch.—It is generally assumed that the broad physical features of the Pacific Coast were largely developed during the prolonged period of erosion between the Miocene and Pliocene, and that these forms have been modified more or less by subsequent movements, both general and local, as well as by subsequent erosion and deposition. During the Miocene the land was depressed, as indicated by the Miocene deposits, the nonconformity between these and the Pliocene deposits showing a period of subaerial

erosion, during which the land was more elevated than at present. This period of elevation and erosion was followed by the Pliocene depression, during which deposits of great thickness were laid down in favorable localities, the larger Miocene valleys being filled to a greater or less extent with deposits which have since been re-excavated to a greater or less extent.

During the post-Miocene erosion interval, it is probable that all the islands then differentiated were mountainous masses belonging to the mainland. Judging from their topography, and the apparent genetic relationships of those of the northern group, the forms then existing probably included all the present islands, except San Nicolas and San Clemente. The latter appears not to have been elevated till the close of the post-Miocene erosion period, or early in the Pliocene depression, and it is probable that the elevation of San Nicolas occurred at about the same time. The disturbance at this time seems to have been general for this whole region, including both faulting and folding, and leading, not only to the differentiation of these two islands, but also, probably, to a greater elevation of all the other islands. Although the forces operative in these movements are believed to have acted intermittently from that time to the present, it is thought that they were mainly effective then, and that any later movements have been of minor importance in relation to the general movements of the California coast, since the highest elevated terraces of San Clemente and the leveled summits of Santa Catalina and Santa Rosa still closely correspond in altitude with the highest terraces on the mainland, and, going further north, with the upper limit of the Pliocene delta deposits along the Tres Pinos Creek.*

The post-Miocene elevation of the coast was followed by the Pliocene depression, during which the sea stood for a long time some 1,500 feet below its present level, as shown by the highest terraces, the planation of the island summits, and the delta deposits just referred to. Whether this was the full extent of this depression for the southern coast, can not be stated from the evidence at present available. During this depression, at first Santa Catalina,

*See, Lawson, The Post-Pliocene Diastrophism of the Coast of Southern California, Bull. Dept. Geol., Univ. Calif., Vol. I, No. 4, 1893, p. 153.

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*See, Lawson, The Post-Pliocene Diastrophism of the Coast of Southern California, Bull. Dept. Geol., Univ. Calif., Vol. I, No. 4, 1893, p. 153.

San Clemente, San Pedro Hill, Santa Cruz, and Santa Rosa all probably existed as islands, or in the case of Santa Cruz and Santa Catalina, as two or more small islands. At this level the ocean remained, cutting away the tops of these islands, till, in the case of San Pedro Hill and perhaps of Santa Rosa, also, they were probably wholly truncated, leaving submarine banks, like those of the region to-day. It is possible that San Nicolas was also above sea level at that time, and has since been planed off to its present lower level. Of San Clemente there remained a small nucleus, near the center of the northern half of the island. Santa Catalina was reduced to a small island lying to the north of the center of the present larger division of the island, with, probably, one or more distant rocks or smaller islands, toward the present extremities of the island. Santa Cruz, at that time, probably existed as a single narrow island, or a line of islands, with a length of at least seven miles, and formed from the northern ridge of the western or main division of the present island. Then, as now, Santa Cruz was probably the highest, if not the largest, of the existing islands.

This depression was followed by a post-Pliocene elevation, as shown both by the present elevation of the Pliocene deposits, and by the elevated coastal terraces. Dr. Lawson* has described one general elevation of the coast in post-Pliocene times, while two such elevations, both greater than the present, and with a depression of 1,200–1,500 feet between them, have been advocated by Dr. Fairbanks.† A more thorough knowledge of the geology of the coast as a whole can alone decide between these two hypotheses. The writer is inclined, from present information, to the view of one general elevation of the California coast in post-Pliocene times, accompanied by minor oscillations, and by local differential movements, such as that called for, for example, in the formation of San Francisco Bay. According to Fairbanks,‡ re-excavation

*The Post-Pliocene Diastrophism of the Coast of Southern California, Bull. Dept. Geol., Univ. Calif., Vol. I, No. 4, 1893; and The Geomorphogeny of the Coast of Northern California, Bull. Dept. Geol., Univ. Calif., Vol. I, No. 8, 1894.

†Oscillations of the Coast of California during the Pliocene and Pleistocene, Am. Geol., Vol. XX, October, 1897, pp. 213–245.

‡Loc. cit., p. 245.

of the Pliocene valley deposits was largely accomplished during the first post-Pliocene elevation, while the coastal terraces were formed during the second. If the deposits along the Tres Pinos Creek are of Pliocene age,* then, since a well-defined series of stream-cut terraces has been developed in these gravels by the stream which has trenched the present valley, and from the upper limit of the deposits down, a single general elevation since these deposits were laid down would seem to be indicated. For it is reasonable to suppose that these stream-terraces were formed at the same time as the coastal wave-cut terraces; and since such a series of stream-cut terraces, on the sides of a narrow valley, could not well be formed after the valley as a whole (or even in large part) had been carved, the present form of this valley, at least, must have been developed during the elevation of the coast which gave rise to the series of wave-cut terraces. The same will hold true for other valleys of the coast where Pliocene deposits have been terraced by stream cutting.

It is generally assumed that, to produce terraces along a sea coast, periods of movement must alternate with periods of comparative quiescence. If variation in movement must be postulated, in order that terraces may be formed during a general elevation, we can not limit these variations to periods of temporary cessation of movement or irregularity in the rate of upward movement, but we must also include the possibility of reverse movements. For, the same causes which give rise to cessation or variation in rate of motion may also be capable of producing reverse movements,—for example, oscillations or movements of depression during a general elevation,—and the possibility of such oscillations must be taken account of in any working hypothesis.

Such oscillations would explain the presence of Elephas remains on Santa Rosa Island. For, irrespective of variations in the height of the submarine ridge at the eastern end of the Santa Barbara Channel (see page 204), an elevation somewhat above the present level would be required to connect Santa Rosa with Santa Cruz Island, and thus with the mainland; while a depression on the

*See, Lawson, The Post-Pliocene Diastrophism of the Coast of Southern California, Bull. Dept. Geol., Univ. Calif., Vol. I, No. 4, 1893, p. 152.

coast below the present sea level would appear to be indicated by the deposits on Santa Rosa in which these remains are found. It should be noted that the only fossil, other than vertebrate remains, which has been described as occurring in these deposits is a fresh-water mollusk (Physa).* It is evident, from the meager descriptions which we have of these deposits, that they should be more thoroughly examined before any definite conclusions concerning the latter coastal movements can be drawn from them.

It is probable that, while the oscillations of post-Pliocene times have been sufficient to connect the northern islands with the mainland, none of the southern islands have had such connection since the post-Miocene period of erosion.

The most recent movement of the coast, as indicated by drowned valleys and submarine features, is a comparatively slight depression, the evidence for which, on the southern California coast, has already been given in detail. The later history of the coast seems, therefore, to be most satisfactorily summed up in a single post-Pliocene elevation, interrupted by minor reverse movements, of which this most recent depression is probably one.

Whether or not future investigation shall lead to modification of the details of the coastal movements as here outlined, is immaterial to the main conclusions of the present paper, the principal point which it aims to establish being the fact that the latest *general* movements of the islands and coast line of southern California have been the same.

University of California,
June, 1900.

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*Am. Geol., Vol. V, 1890, p. 51.

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THE GEOLOGY

OF THE

CENTRAL PORTION OF THE ISTHMUS OF PANAMA.

BY

OSCAR H. HERSHEY.

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INTRODUCTION.

Because of the richness of its undeveloped mineral resources, the complexity of the problems presented by its geologic phenomena, its comparatively easy accessibility, and its forming a connecting link between the two great divisions of the American continent, the Isthmus of Panama seems destined to be of exceptional interest to students of geology. During about three months in the early part of the year 1898, the writer was engaged (incidental to prospecting for the precious metals) in a somewhat desultory investigation of the geologic history of the central portion of the Isthmian country, traveling about 1,000 miles by schooner, canoe, horseback, and afoot, and although the time was hardly sufficient to gain a very comprehensive knowledge of the subject, it resulted in the discovery and partial exploration of several formations earlier in age than any yet reported from the Isthmus.

Great obstacles to the pursuit of geological study in such a tropical land as the Isthmus of Panama are presented by the density or jungle-like character of the vegetation in large portions of the low plains and in certain high mountainous areas where rain falls at least once during every day in the year; by the enervating effect of the warm moist atmosphere, which dulls the intellect and decreases the power of observation, destroying the zest for knowledge, which is the real incentive to scientific progress; by the scarcity and in portions of the country total absence of roads or even a path or trail; and by the long delays consequent on life among a people characterized by a lack of energy. In illustration of the first statement, I will mention that one morning I climbed a high tree and from its branches learned more of the geology of the vicinity in ten minutes than I had in the preceding several days of travel in the forest.

In January, 1895, Mr. Robert T. Hill examined a section across the Isthmus on the line of the Panama railway and canal, and another across Costa Rica between Punta Arenas and Port Limon. The results are given in his admirable paper entitled "The Geological History of the Isthmus of Panama and Portions of Costa

Rica." * My study was made independently and without a knowledge of his, and to a certain extent covered the same ground, but in the following pages I shall endeavor to avoid traversing matter already treated at length by him, and add only new material to the literature of Isthmian geology.

The oldest formation observed by Mr. Hill on the Isthmus of Panama is a water-laid rhyolitic and trachytic tuff, by him named the Panama formation. I was fortunate in accidentally discovering a series of formations under and consequently older than the Panama formation. Part of this series represents an old land which once existed mainly to the southward of the present Isthmus. Mr. Hill had suggested that such an ancient land occupied the position indicated, and my happening upon a remnant of it was a remarkable confirmation of his hypothesis.

It is unfortunate that the strenuous conditions of my journey prevented the collection and submission to paleontological specialists of sets of fossils from the pre-Panama formations encountered. Marine fossils were observed in a number of places, although generally imperfect. My failure to secure specimens leaves this open as a splendid field for some enthusiastic collector. Some of the localities will be mentioned in the following pages.

The absolute determination of the age of the earlier formations must be left for future students, but I will ask the indulgence of the reader to remarks showing what correlations are indicated by the lithology, structure, and sequence of the strata. There is a remarkable similarity between several formations on the Isthmus of Panama and a series of probably late Jurassic and Cretaceous age in California. I submit that it is not a mere coincidence, but that they have been formed under like conditions, at about the same time, and subsequently subjected to about the same amount of metamorphism.

AREA STUDIED.

The Isthmus of Panama, generally considered as coextensive with that political division of the Republic of Columbia, officially

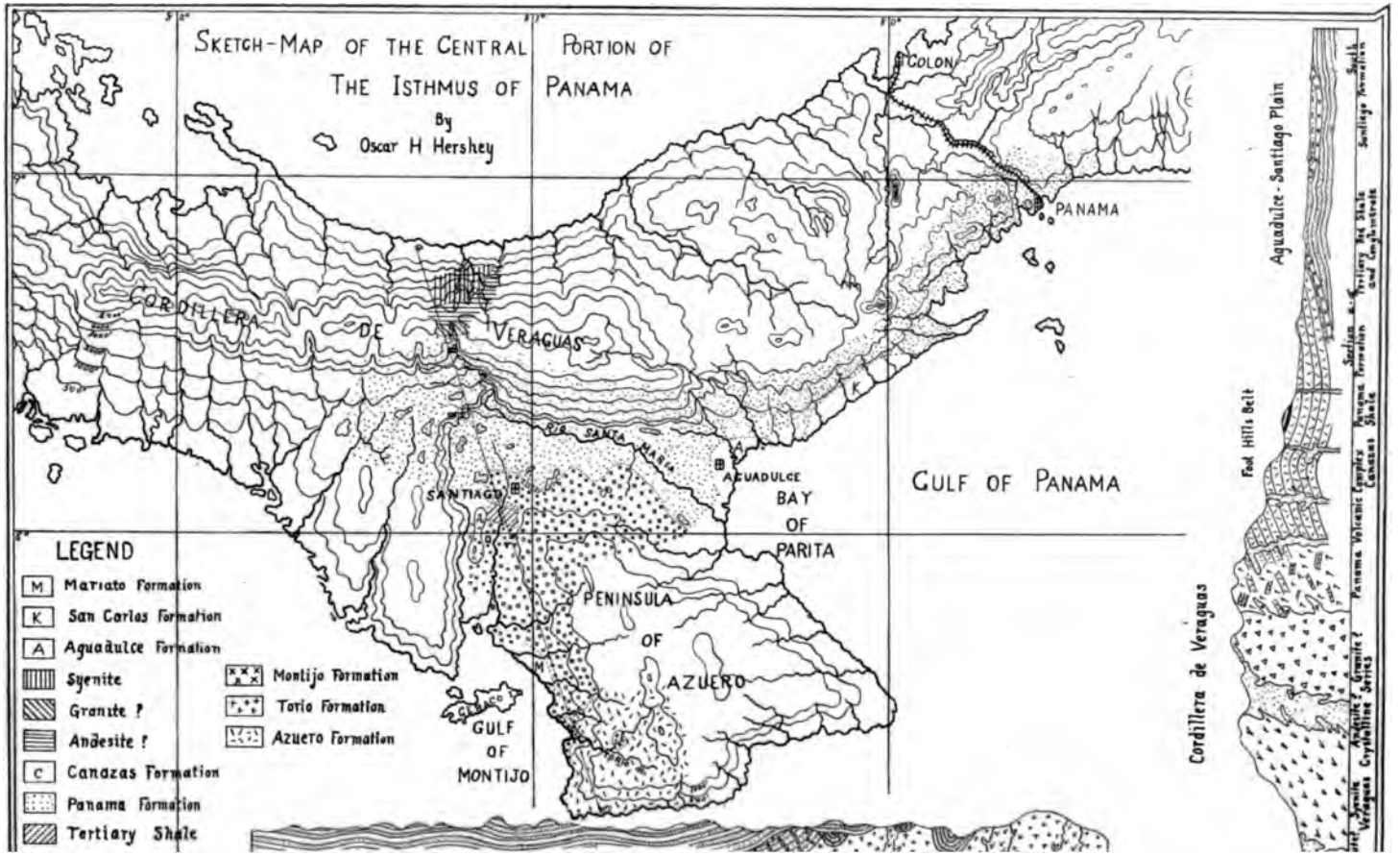
* Published as Bulletin No. 5 of the Museum of Comparative Zoology, at Harvard College, Vol. XXVIII.

styled the Department of Panama, a strip of land about 400 miles in length and 40 to 120 miles in width, with a probable average of about 75 miles, is too large and diversified to be handled as a unit, and may conveniently be divided into sections. It is the middle section, characterized by high, abrupt mountains, peculiar rounded hills and low plains, extending from the canal in a general west-southwest direction to a distance of about 150 miles from Panama, that is the subject of this paper. About 100 miles southwest from Panama, the broad Peninsula of Azuero projects southward about 60 miles from the main body of the Isthmus. It is the oldest part of the Isthmus country. West of it the coast is very irregular, being indented by many bays, some of which are long and narrow and beautiful examples of "drowned valleys." Off the southern coast are many high mountainous islands.

The chief section which I examined extended across the widest portion of the Isthmus from Punto Mariato, the southwestern extremity of the Peninsula of Azuero, till within five miles of the Caribbean Sea, or directly through the center of the largest tract of the Isthmus marked on recent maps as "unexplored." This was directly across the strike of the strata, and it is believed that all the principal formations developed in the district were seen, and the geological history is known with a reasonable degree of completeness. As Mr. Hill found, it is the general rule on the Isthmus that the formations become newer from south to north.

TOPOGRAPHY.

From the head of the Bay of Parita, 90 miles west-southwest from Panama, there extends westward along the Isthmus a distance of about 50 miles and over a width averaging about 20 miles, the most beautiful peneplain of small extent which I have ever seen. Nearly all parts of it must originally have been a perfectly base-leveled plain dotted with many monadnocks from 50 to 500 feet in height. Around the head of the Gulf of Montijo and near the foot of the mountains north and west of Santiago the plain is much dissected by cañon valleys of no great depth and often of considerable width. The interstream portions are llanos, or grassy plains, and on them live a large part of the inhabitants of the Isthmus.


SKETCH-MAP OF THE CENTRAL PORTION OF THE ISTHMUS OF PANAMA
By
Oscar H Hershey
COLON
PANAMA
CORDILLERA DE VERAGUAS
RIO SANTA MARIA
SANTIAGO
AGUADULCE
BAY OF PARITA
GULF OF PANAMA
PENINSULA OF AZUERO
GULF OF MONTIJO
LEGEND
Mariato Formation
San Carlos Formation
Aguadulce Formation
Syenite
Granite ?
Andesite ?
Canazas Formation
Panama Formation
Tertiary Shale
Montijo Formation
Torio Formation
Azuero Formation
Cordillera de Veraguas
Aguadulce - Santiago Plain
Fault Hills Belt
South
Tertiary Bed Shale and conglomerate
Santiago Formation
Sedimentary Formation
Panama Volcanic Complex
Canazas Shale
Veraguas Crystalline Series

The town of Santiago de Veraguas is centrally located on the western part of the plain and Aguadulce is an important place near its eastern border.

This remarkable inland topographic depression is bounded on the north by a high, steep chain of mountains, which is the primary axis of this portion of the Isthmus and bears the name of the Cordillera de Veraguas. The system is made up of exceedingly steep, narrow ridges, which mostly rise to a height of about 5,000 feet but further westward attain elevations of 8,000 and in the volcanic peak of Chiriqui 10,500 feet, and form a chain trending in a general east-west direction parallel with and close to the Caribbean coast. It is the eastward extension of the main plateau of Costa Rica, but has here been more deeply trenched by erosion. The change from the low plain on the south to the high sierra is effected by a series of lower mountains (montañas) or foot-hills, whose summits gradually rise from the level of the monadnocks on the plain to the crest of the cordillera.

On the north of the main chain, the surface descends very rapidly to a dissected plain, which slopes more gradually to the sea, two to five miles distant from the foot of the sierra. This also is a dissected plain of erosion. The streams issue from the deep mountain valleys and flow across it in narrow rocky cañons.

Southward from the Aguadulce-Santiago plain lies the mountainous land of the Peninsula of Azuero, but its central range, the Sierra Guanico, trends north-south, being therefore at a right angle to the Cordillera de Veraguas. From the axis of the peninsula, along which the sierra attain altitudes of 2,000 to 3,000 feet, the mountains descend in sloping spurs eastward to the Bay of Parita and on the west to the Gulf of Montijo. From some points of view the interior of the peninsula seems to be occupied by several parallel north-south mountain ranges with irregular crest lines, being sometimes reduced to a range of mere hills and again rising to mountain ridges several thousand feet high. On the west of the Gulf of Montijo the mountains are not quite so high but are equally irregular and the main range has a north-south trend, terminating in low hill ranges on the south of the Aguadulce-Santiago plain. In the gulf are several large hilly but not mountainous islands,

which are elevated above remnants of a low coastal plain which once occupied the site of the gulf.

On the west of the Aguadulce-Santiago plain, by the increase of the monadnocks into a group of pointed hills occupying most of the surface, a more elevated, broken country is produced, which separates this plain from the plain of David in the province of Chiriqui. Thus the former plain is surrounded on three sides by mountainous tracts and is only open to the sea at its eastern end.

Eastward from the head of the Bay of Parita, the Cordillera de Veraguas, with its spurs, occupies the greater portion of the Isthmus (the coastal plains being limited to narrow strips), until about 20 miles west of the line of the Panama railway and canal, where the high sierra abruptly terminate and a different type of topography prevails eastward.

The topography of the country in the vicinity of the Panama railroad between Panama and Colon has been so ably discussed by Mr. Hill that I will avoid retraversing the ground except to make a few general remarks. Like the preceding observer, I was strongly impressed by the fact that there is not along this portion of the Isthmus a well-defined central range such as geographers have pictured as a connecting link between the Cordillera of North America and the Andean chain of South America, but rather a great group of peculiar pointed hills, extending from the islands in the Gulf of Panama, two-thirds of the way across the Isthmus, and which may be described, where not too closely grouped, as monadnocks rising from a low base-level developed on both sides of the Isthmus but nowhere greatly elevated above the sea. I was also impressed by the ancient type of the erosion topography and by the great depth of weathering. It is beyond question that this portion of the Isthmus has not been submerged at so late a period as the Pleistocene, and, in fact, it has been a remarkably stable portion of the continent since rather early in the Tertiary era.

FORMATIONS EARLIER THAN THE PLEISTOCENE.

The Azuero Formation.—So far as now known, the oldest rock on the Isthmus of Panama is a green eruptive formation. It is in the form of a *massif* of unknown but immense thickness, which

seems to occupy the entire southern part of the Peninsula of Azuero, forming important mountain masses in the interior and exceedingly ragged cliffs on the coast. It is beautifully exposed on the shore of the Pacific Ocean on the west side of the peninsula, both north and south from the mouth of the Torio River. Here it is a massive fine-grained crystalline of very basic composition and a characteristic green color. Unfortunately, my petrographical knowledge was very crude at that time and no fragment of this rock was brought away. Because of its general resemblance to a Jurassic diabase in northern California, I discriminated it as a diabase, but I am now more inclined to believe that it is a peridotite, although nowhere prominently serpentinized. One of the principal constituents is a semi-vitreous, transparent mineral of a greenish gray color which may be olivine.

An important part of the eruptive mass is an equally fine-grained but dark brown and black rock, which under a hand microscope was seen to be composed of black crystals of hornblende and a lesser quantity of light brown feldspars, and hence resembling a diorite. This appears to be in the form of huge dikes cutting the green rock. The whole formation is streaked by many exceedingly irregular veinlets of white quartz and calcite. Some veins contain a red mineral of the color of cinnabar, but the staining matter is probably iron oxide.

Up the Torio River, the green rock sometimes assumes a schistose character, sometimes that of a non-laminated slaty rock, and again is clearly an eruptive. It is possible that the complex may include highly metamorphic sedimentaries. Everywhere it is characterized by the veinlets of quartz.

By far the most peculiar thing connected with this formation is certain large irregular masses of structureless, hard, bright red quartz which are of frequent occurrence in the green rock near its contact with later formations, and in the interior of the peninsula has weathered out and lies in great boulders in the bed of the Torio River. Some of these masses contain hundreds of cubic feet and others seem to occupy ancient fissures several feet wide. The only thing closely resembling this quartz or chert that I have ever observed is heavy-bedded portions of the radiolarian cherts of the

Franciscan series in California, but the occurrence appears to be different except that in a few cases the latter also have been invaded by and are enclosed in eruptives.

The age of this igneous complex will be discussed after the succeeding formation has been described.

The Torio Limestone.—The next formation seen in going up the coast from the Torio River is a hard, light gray, massive limestone. It is sometimes nearly pure and is then sub-crystalline. More often it is very impure but its outcrop always reveals its calcareous character. In places it abounds in fossils (mostly shells of marine brachiapod or lamellibranchiate species) which are so cemented into the rock that they can not be separated from it. In a few places the rock is a regular breccia-conglomerate of fossils and rock fragments from older formations, including the green igneous rock. Like the preceding formation, it is exceedingly well supplied with irregular veinlets of white quartz and calcite, which are not common in any succeeding formation. It is impossible to tell the thickness of the limestone, but it is at least several hundred feet. The strike of the formations along this coast is generally parallel to the beach, and hence it is difficult and often impossible to determine their thickness.

Limestone is exposed along the coast at low tide in several small irregular patches. In the case of the most southerly ones it is surrounded by and appears to overlie the igneous *massif.* At several places it is exposed very close to the latter and contains strata of conglomerate which dip away from the contact and which contain fragments of the green igneous rock; hence, it is evidently newer than the latter.

This limestone is well exposed on the Torio River, a few miles from the coast, in many irregular patches of light gray limestone, some of which are of small extent and others quite important. It is here always well stratified, being moderately thin-bedded and dipping steeply in one or another direction. It clearly overlies the green igneous formation, but along the contact is much contorted, and masses of dark gray diorite of fine grain but distinct holocrystalline structure, have been injected into the limestone.

The green igneous rock and the limestone are closely related in

age and have had the same life history since they were formed. Together they have been subjected to mountain building forces, being irregularly folded and faulted, and dyke rock injected into the fissures; they have been metamorphosed to the same extent; and they both have the abundant irregular veinlets of white quartz and white calcite, indicating general fracturing. So far as appearances go they are much older than any other formation yet found on the Isthmus.

While examining the green eruptive I was impressed by a marked resemblance in many particulars to a diabasic formation of Jura-Triassic age in northern California, and thought the entire complex including the limestone might be of Jurassic age. The fossils in the limestone seemed not of types common to Carboniferous or older faunas, but appeared to be of a somewhat newer facies. For reasons which will appear later, I had to place this formation earlier than the late Cretaceous and hit upon the Jurassic as the age best indicated by the evidence. Lately, upon becoming acquainted with the characteristics of the Franciscan series of the Coast Range region of California (thought by Lawson to belong somewhere in the interval between the recognized typical Jurassic and the typical Cretaceous formations), I have recognized the fact that the Azuero-Torio complex and the Franciscan series have had an identical life history since their formation; that is, they have suffered the same orographic disturbances, alterations of a like degree and like character, and are separated from newer formations of known age by non-conformities of equal value.

Now, ordinarily lithologic resemblances are too uncertain a means of correlation in such widely separated districts as the Isthmus of Panama and California, but as suggestive of what correlations will finally be made, let us assume that the oldest series on the Peninsula of Azuero represents the same late Jurassic or early Cretaceous sediments and eruptives as the Franciscan of California, that the alteration of one was part of the same metamorphic action as that of the other, and that the land area following the deposition of the Torio limestone and injection of diorite in the Isthmian region, represents the same epoch of the early Cretaceous

as the land area indicated by a non-conformity between the Franciscan and Knoxville of California. We will provisionally adopt this as a basis upon which to build up our Isthmian column of formations and will see how we will come out at the top or when we reach a formation whose age has been fixed by study of its fossils.

The Montijo Conglomerate.—On the eastern shore of the Gulf of Montijo, opposite the island of Cebaco, about one mile north of the Torio River, there is a great formation, hundreds of feet thick, of fine conglomerate, hard and gray in color. It is well stratified and dips usually at a high angle. There are occasional fossils, but, I fear, too imperfect for specific identification. Coarse conglomeraate and fine sandstone are both rare. The outcrop in the sea has a reddish tint.

The conglomerate formation is newer than the Torio limestone and is distinctly seen to rest on it. Between them is an important non-conformity. The green eruptive and limestone were contorted, faulted, the fissures filled with diorite, the white veinlets formed a larger part of the metamorphism accomplished, and the whole complex reduced by erosion from a mountain mass to comparatively low ground before the Montijo conglomerate was deposited on the submerged borders of the old land. This will rank with the great non-conformities in the United States. It appears to be of the same value as that separating the Franciscan and Knoxville series in California, and we will provisionally correlate the Montijo conglomerate with the latter formation of known early Cretaceous age.

The Montijo conglomerate is separated from the next newer formation by a non-conformity represented by a tilting of the formation and sub-aerial erosion. This was not nearly so long as the preceding erosion interval and appears to be of the same value as that separating the Knoxville and Chico in the Coast Range region of California. We shall, therefore, expect to find some evidence of the Upper Cretaceous age of the succeeding formation.

The Santiago Formation.—At the town of Santiago de Veraguas, where first discriminated, this is made up of thick layers of non-laminated shale of a dull greenish gray color and a peculiar breccia and breccia-conglomerate. The latter are characteristic of this

formation, being found nearly throughout its extent. Although there are some thin layers of fine gravel and sand, the great mass of the formation is a shale, everywhere characterized by the same dull greenish or olive tint. It is not hard rock, yet is sufficiently lithified to be used as a building stone. It contains but little iron and weathers usually into a yellow clay soil. In some places it abounds in fossils which are generally imperfect and so brittle as to be incapable of preservation. They are of marine species of gasteropods, lamellibranchiates and allied forms. They differ decidedly from the species at present so plentiful on the Pacific beach of the Isthmus, but certainly are not of such old types as the Carboniferous or Jura-Trias. As I remember the fauna it more nearly resembled the Chico than that of any other formation, but I can not say that they are specifically identical.

The Santiago formation forms the foundation of the entire Aguadulce-Santiago plain, over a large portion of which it is the surface formation. Here it always dips in some direction, but rarely at a high angle. It seems to have been formed into low folds and was perhaps faulted in places. It is extensively developed in the northern half of the Peninsula of Azuero, where it forms mountains. On the eastern shore of the Gulf of Montijo it can be traced south until it is seen to overlie the formations previously described in this paper. In this direction it loses its breccia beds, becomes more sandy, better lithified and titled at a high angle, even in places standing on edge. On the lower two miles of the Torio River and at a promontory a short distance south of the mouth of the stream, it is exposed in beds of hard sandstone and shale over one thousand feet in thickness and dipping steeply in a general westerly direction. Here it is in contact with the green igneous formation, fragments of which, particularly the red chert, are included in its basal breccia-conglomerate. Farther north it is seen to rest unconformably on the Montijo conglomerate and nearly abuts against and caps a boss of Torio limestone.

The non-conformity at the base of the Santiago formation is of the same general nature and probably the same time value as that which separates the auriferous slate series and the Chico series in northern California. All the preceding formations, no matter how

they may have been forced up into mountain masses, had been reduced by erosion to a comparatively low land much of which was a slightly rolling plain—a Cretaceous (?) peneplain—and upon this comparatively plain surface after submergence, the Santiago sandstone and shale were deposited and the breccia-conglomerate formed by combined wave and current action.

There are, perhaps, nowhere on the American Continent two formations, so widely separated, so nearly resembling each other as the Santiago series on the Isthmus of Panama and the Chico series in the western part of Shasta County, California. They are identical in composition, texture, lithification, color and relations to older and newer strata. It seems hardly possible that all the conditions of their deposition and subsequent history could have been so nearly alike unless they date from about the same period. We will, therefore, provisionally correlate these formations and assume that the deposition of the Santiago formation closed the Cretaceous period.

The Tertiary Basal Conglomerate.—On the Aguadulce-Santiago plain, apparently occupying broad shallow depressions in the Santiago formation, there are large patches usually elongated from northwest to southeast and having widths of one to five miles, of a series of newer and softer formations. Southwest from Santiago the basal formation is a conglomerate of dark dull red and brown color, often well lithified and always distinctly a rock as distinguished from mere gravel. In places it contains a few imperfect fossils. It is exposed to considerable thickness and may be 50 to 100 feet, but evidently varies much from place to place. It always dips decidedly but rarely very steeply toward the center of structural depressions. Eastward from Santiago it is reduced to 10 to 25 feet of a rather coarse, moderately well indurated, heavily-bedded sandstone of a dark purplish tint.

The Tertiary Red Shale.—Resting conformably upon the conglomerate is a thin formation (10 to 50 feet, averaging about 25 feet) of soft shale and clay, bright red and dark reddish brown in color, without fossils, and generally laminated but readily weathering into structureless clay. It is persistent throughout the plain wherever its horizon is exposed.

About five miles north of the port of Montijo, this red shale has been baked by the intrusion of an eruptive not exposed, into a bright red mica schist as ancient in appearance as Archæan schists in the United States, and sufficiently extensive to have a considerable road cutting entirely in it. This is one of the finest cases of contact metamorphism of comparatively recent date known to me.

The Panama Formation.—In the country southwest of Santiago there is above the red shale a harder, more massive formation, usually of lighter color. It varies from white through gray to a dull purplish tint. Never is it laminated but sometimes it is seen to be heavy-bedded. Macroscopically it appears to be composed of a fine granular material. I consider it largely a water-deposited fine volcanic ash or rhyolitic tuff. In places it is coarse-grained and even slightly conglomeratic, in which cases it is well indurated. Where not eroded the thickness is probably at least several hundred feet.

East of Santiago there is, above the red clay, a great series of usually soft and chalky, non-laminated but water-deposited, fine-grained, clay-like materials (rhyolitic and trachytic tuffs) of a color prevailingly white to gray and rarely red or brown. This white, chalky deposit has been penetrated at the Remanse mine to a depth of over 600 feet, but contains layers which weather out like lava. East of the Santa Maria River the formation is widely developed, although many of the small hills which stand on the plain appear to be composed of trap rocks such as diorite, porphyry, basalt, etc.

The series of soft formations over the Santiago shale, consisting of the purple basal conglomerate, the red shale, and the white and light gray semi-massive tufaceous formation, are conformable to each other, were laid down in immediately succeeding epochs in the same body of water and belong to the same period of geologic time. This was separated from the epoch of deposition of the much harder and older-appearing Santiago formation by a considerable erosion interval, during which was formed the broad shallow basins in which the Tertiary strata are now found.

In its rhyolitic composition, prevailing white color and chalky texture (but not its heavy bedding) the Panama formation more nearly resembles the lower 1,000 feet or volcanic division of the

Monterey formation (of Miocene age) developed extensively in the Coast Range region of California, than any other of that state. Both mark an epoch of very acid volcanic eruptions in their respective regions. However, the erosion interval at the base of the Isthmian Tertiary series hardly indicates a time sufficiently long to cover the whole or even any large part of the Eocene period, and we will, therefore, provisionally place the Panama formation in the early part of that period.

In all the formations which I have described, no clear evidences of volcanic action of a modern character are to be seen until we reach this last formation, which seems to be made up essentially of fine ashes. To the epoch of acidic volcanic eruptions, there ensued one of highly basic eruptions. The products of the latter occur chiefly in the form of plugs, dikes, sills and laccolites of diorite, andesite, basic porphyries and basalt which occur throughout the area of the rhyolitic tuffs and are even scattered through the red shale, basal conglomerate and the Santiago formation. These hard rocks resist erosion better than the tuff and crop out like dikes and bedded sheets, form most of the knobs and cap the peaks. Boulders derived through their partial decay are scattered all over the volcanic region.

It is a series of rocks of this character which forms the foot-hills of the great range of the Cordillera de Veraguas, north of Cañazas and the Remanse gold mine, over a belt about 20 miles wide. This was the region of chief volcanic activity, and in it the deposits are of great thickness. Here the basic intrusives make up a large part of the entire formation. In addition to the fine volcanic ashes, there are thick deposits of coarse gray ashes, much of which has the macroscopic appearance of a massive rock and is not water-laid. In fact, in this foot-hills belt the direct volcanic products of the rhyolitic and the basaltic epochs are so confusedly intermingled that it seems advisable to consider them as a unit and treat of them under the comprehensive term, the *Panama Volcanic Complex.*

This Panama series continues northeastward beyond Aguadulce, between the narrow, low, coastal plain and the high sierra, and is developed and well exposed in the vicinity of Panama. Between

here and the Culebra cutting on the proposed Panama Canal it has been studied by Mr. Hill and by him named (excluding the intrusives) the Panama formation. Microscopic examination shows that the early water-deposited portion in large part consists of a soda-rhyolite tuff or a soda-trachyte tuff.* The basic intrusives and their associated ash beds are strongly developed in the vicinity of Culebra, where they include such types as "basalts (olivine, diabases, and dolerites), augites (?) (both andesitic and porphyritic) and trachyte tuffs of similar materials, and one boulder bluff of hornblende augite (?), andesite, or porphyrite." Mr. Hill also makes the acidic distinct from and older than the basic eruptive epoch.

Now, subsequent to the intrusion of the Panama formation by these basalts and andesites, their débris was formed into the Bujio conglomerate, which is the basal formation of a series of sedimentaries developed on the Atlantic side of the Isthmus. The age of these formations is definitely fixed by abundant fossils. The range is from the Claiborne stage of the Eocene merely as far as the early Miocene, when sedimentation ceased in the Isthmian region and was not resumed until the early or middle Pleistocene. On the strength of this evidence, Mr. Hill correlates the basic volcanic epoch with the late Eocene and considers the Panama formation proper of considerably earlier age, probably Cretaceous.

There is no positive evidence of the pre-Eocene age of the Panama formation. As a matter of fact, it is my impression that the deposition of the rhyolitic tuff did not long precede the intrusion of the basalts and andesites. As the latter, we now know, occurred rather late in the Eocene period, we may reasonably place the former early in the same period. We will then divide the history of the Eocene period as follows:—

1. A short epoch of erosion.

2. An acidic volcanic epoch with partial submergence of land, and deposition of Panama formation proper in sea on borders of the volcanic range.

3. A basic volcanic epoch, with intrusion of Panama formation

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* Determination by Turner from specimens submitted to him by Mr. Hill. See paper by latter, page 201.

and continuance of eruptions along volcanic range (Veraguas foot-hills belt and Culebra region).

4. The Claiborne epoch of sedimentation on Atlantic side.

This classification of the volcanic formations brings the Santiago formation precisely in the latter portion of the Cretaceous period, where we provisionally placed it because of its remarkable resemblence to the Chico formation of California, and seems to indorse our tentative correlations down to the very lowest formation.

The Cañazas Formation.—The village of Cañazas is situated in the foot-hills belt in the midst of mountains composed of the Panama series of volcanics. Beginning at about one mile east of the village, there is a small area, several miles in diameter, of finely laminated light gray and brown shale. It is evidently composed of volcanic ash which was deposited in a body of water, probably a small lake. There are slight traces of fossils. In the midst of the shale is a three-foot stratum of coarse volcanic ash, representing apparently a single shower. On the eastern and northern sides of the area, a coarse basal conglomerate composed of water-worn boulders of the lower portion of the volcanic series, is developed to a thickness of 50 to 100 feet. The formation dips southward 10° to 30°, having been concerned in the orographic movement which lifted the Cordillera de Veraguas. It is evident from the way in which the Cañazas formation is included in the Panama series that it represents local conditions—merely a lake of short duration in which was deposited several hundred feet in thickness of finely laminated tuff or shale. Its age is, therefore, probably Eocene.

The Veraguas Crystalline Series.—The Cordillera de Veraguas, where I crossed it on the line of the old Santa Fe and Cocuya trail, about 120 miles west of Panama, is an immense igneous mass, probably 25 miles in width and attaining an altitude of 5,000 feet above the sea. It is made up of three rock types, specimens of which were submitted to Dr. U. S. Grant, who determined them. In the valley of the Rio Santa Maria on the southern slope of the range, the formation is mainly a rather coarsely crystalline plutonic rock of light yellowish gray color. With its abundant free quartz, it somewhat resembles a true granite on outcrop. The

interior is hard and often horizontally jointed, giving it a quasi-stratiform appearance. This was identified as rhyolite, but the fragment examined was small, and although the rock has the composition of a soda-rhyolite, its occurrence as an intrusive, and its coarse granitic structure, would seem rather to entitle it to be termed an alkaline granite.

The bulk of the main range or Sierra Balcazar, at the head of the Santa Maria River, was found to be composed of a very hard dark gray massive rock, which has been doubtfully identified by Dr. Grant as andesite, although upon closer examination, he thinks, it may prove a trachyte or even a diabase. In places it contains large phenocrysts of hornblende. This andesitic rock occurs in the deep valley of the Guaxaro River on the north of the divide; but a few miles farther north, a ridge nearly equally as high as the main divide, separating the Guaxaro from the Bijuco and Saltos Rivers, is composed to the very top of a massive coarse crystalline. This same rock is exposed to low levels in the valley of the Bijuco River. Dr. Grant says it is "composed mostly of flesh-colored feldspar, with some biotite and perhaps a little hornblende or augite," appearing like some of the nepheline syenites.

A little farther northeast, the Saltos and Santiago Rivers are flowing over precipices and huge boulders of the fine-grained dark gray and black andesite(?). The relation between the three rock types was not well made out, as the country is a dense jungle, but in general it may be said that the coarse crystallines form the core of the cordillera and the andesitic rock occurs as a thick coat originally completely covering them, but largely removed by erosion.

It is probable that the acid crystallines occur in the form of huge batholites which invaded the supposed andesite. But for evidence of their having been intruded subsequent to the late Eocene basic eruptive epoch, they might be supposed to represent the plutonic phase of the same volcanic activity as produced the Panama formation. Doubtless, these Veraguas crystallines (syenite and alkaline granite) belong to the same system of "pseudo granite or syenite" rocks mentioned by Hill as exposed in the plateau of Costa Rica, the Sierra San Blas, around the Sierra del Marta, on

the South American mainland, and at several places in the Antilles, "which have been pushed up into the Tertiary strata, and now form the core of great mountainous protuberances." The age of these syenitic batholites is variously given as "mid-Tertiary" and "late-Tertiary." It is probable that it was the uplift of the Isthmian Territory due to the upthrust of the crystalline magmas of the Cordillera de Veraguas and the Sierra San Blas which ended the Tertiary sedimentation along the Panama Canal section, and hence it may be provisionally considered middle Miocene in age.

RESUMÉ OF THE PRE-PLIOCENE ISTHMIAN HISTORY.

The "old land" or early representative of the Isthmus of Panama lay mainly south of the present Isthmus. That it was a land mass of considerable extent, is indicated by the heavy beds of conglomerate formed from it. Its formations and history are remarkably like those of the Coast Range Region of California, but it will probably be more advisable to connect it with the Andean Region on the south. The north-south ranges of mountains of this old land may have been members of the system of Andean ridges known to be of Cretaceous age and to be made of just such rocks as those of the Peninsula of Azuero. The eastern members of these parallel north-south mountain ranges of Cretaceous age persist in the northern portion of the present Andean region, but the western members we may suppose have been destroyed by erosion and subsidence, except this small remnant constituting the Peninsula of Azuero. On the northern border of this old land were laid down the formations which now make up the main body of the Isthmus.

During the Montijo epoch (probably early Cretaceous) the coast was sinking to allow the conglomerate to overlap upon the old land surface. An uplift added a belt of conglomerate to the land, even throwing it up into mountains. Then ensued a long period of sub-aerial erosion during which the mountainous land was mainly reduced to a low undulating plain—presumably a late Cretaceous peneplain. An extended submergence of the coastal portion of this old land mass enabled the accumulation of many hundreds of feet in thickness of Cretaceous(?) shales, fine sandstones,

and the peculiar breccia beds and breccia conglomerates so characteristic a feature of the Santiago formation.

Finally another orographic disturbance again folded the strata of the southern half of the Peninsula of Azuero into a mountain system, tilting the Santiago formation almost to a vertical position. Associated with this movement was an uplift of the sea-bottom on the north of the "old land" and an extension of its limits to at least the northern edge of the Aguadulce-Santiago plain. During the following short epoch of sub-aerial erosion, broad shallow basin valleys were eroded in the surface of the Santiago formation. Early in the Eocene period, the plain was submerged and the Tertiary basal conglomerate and overlying red shale were deposited on its surface. The evidence is very clear that the material was derived from the south. Indeed, I think the "old land" still remained in large part above sea-level, and its red residuary soil furnished the material for the lower Eocene formations.

Now a radical disturbance of the quiet of this land was inaugurated. Far out in the sea, at the edge of the sub-marine shelf which bounded the "old land" on the north, was a line of weakness. Here the earth was fissured along an east-west belt on the site of what is now the southern foot-hills belt of the Cordillera de Veraguas and extending thence east over the site of Panama. Lava and ashes issued from volcanic vents, the latter to be largely deposited in the shallow sea between the volcanic range and the old land. At first the material was very acid, but later came highly basic eruptions. A broad strip was added to the old land merely by the accumulation of igneous débris. Then came an epoch of quiescence, during which the fossiliferous late Eocene and early Miocene sedimentaries were deposited in the sea on the north side of the volcanic range.

The next event was the profoundest disturbance of which we have a record, that has ever affected any part of the Isthmian country. This was the upthrust of the Cordillera de Veraguas to a high mountain range, and the invasion of the volcanic series by huge batholites of alkaline granite and syenite. The old Andean system of orographic disturbances had ceased and instead had come into action, as Mr. Hill has indicated, the Antillean system.

The new folds had an east-west trend and the Cordillera was built across the ends of the old north-south system.

We are now ready to formulate a great principle in the geological history of the Isthmus. From the earliest times of which we have any record to the present day, there has been a tendency toward a southward tilting of the entire country. While a great highland belt was being added to the Isthmian country on the north side of the Aguadulce-Santiago plain and its original far eastward extension, the "old land" area on the south was being destroyed, partly by the action of the sea along the shore and partly by subsidence. The whole of the presumably pre-Cretaceous land area of this region has gone beneath the Pacific's waters, except the southern part of the Peninsula of Azuero, and perhaps a few small areas west from the Gulf of Montijo. Eastward from the Peninsula of Azuero, the sea has swept over the "old land" and the plains belt north of it and in the vicinity of Panama has even invaded the volcanic highland.

DEVELOPMENT OF PRESENT TOPOGRAPHY.

Under this heading it is proposed to outline the chief physiograpic events of the later geologic history of that portion of the Isthmus lying west of the Panama Railroad and east of the province of Chiriqui. The description of the various Pleistocene formations has been reserved for this section of the paper, as their history is inter-related with that of the geomorphogeny of the land surface.

The earliest date with which we are now concerned is the close of the great Panama epoch of volcanic activity. As the Panama series is made up of a vast thickness of consolidated tuffs, with intruded and intercallated sheets, irregular masses, trap dikes and volcanic necks of diorite, andesite, basalt, etc., it may be presumed that the surface at the close of the period was a very uneven one, with a type of topography similar to that so beautifully exemplified in the recent volcanic ranges in Guatemala and Nicaragua; that is, it abounded in cone-shaped peaks and craters, with variously-shaped basins between the individual volcanoes. Through this land of heterogeneous topography the streams were forced to flow hither and yon by the accidents of unequal deposition of ejected

material, as they passed from one basin to another. No relics of this necessarily unsystematic drainage system are left. In other words, in none of the streams of the Isthmus can the determination of the course be traced back to this volcanic period. Indeed, the volcanic cones and craters themselves have all disappeared (except possibly the recent volcano of Chiriqui), and all the medium and minor features of the topography are due to sub-aerial erosion.

The Tertiary Dissected Peneplain.—Soon after I first recognized the cone-shaped elevations and low isolated hill ranges on the Aguadulce-Santiago plain as monadnocks on a Pleistocene peneplain, I noticed that while they vary in height between 50 and 500 feet, nearly all of those in any given section of the plain attain about the same elevation. Many of the hill ranges have comparatively even crest-lines, and a few are flat-topped as though they are remnants of a plain. Indeed, the summits of practically all the monadnocks on the plain will fall naturally in a slightly deformed, nearly destroyed plain. At first I thought this was a constructional plain or the original surface at the close of the volcanic period; but I found that the monadnocks are composed of a great variety of formations, among which I may mention Santiago shale, Eocene red clay, the tuffs of the Panama series and the dikes and volcanic necks of the same. Besides it is impossible that the original surface in such a volcanic region could have been so perfect a plain as is indicated by the summits of the monadnocks. It is quite evident that there had here been some erosion, and the manner in which the supposed plain of the summit level of the hills beveled the edges of the inclined strata suggests peneplanation.

Transferring our attention to the top of the high sierra which bound the view on the north, we find that the Cordillera de Veraguas appears from a distance as an extremely abrupt single ridge, somewhat broken in places by valleys eroded in its flanks, and having a comparatively uniform altitude of about 5,000 feet. But when we travel about within its limits, we find that it is in reality only a deeply dissected plateau. All the adjacent ridges rise to about the same height and often have even crest-lines for several miles. There are some extended flats at the level of the mountain summits, as the high llano on which flows the upper stretches of the Rio de

Los Saltos. The valleys are merely deep, narrow, steep-sided ditches carved from the plateau by the streams. Eliminating them, the whole country over a width of about 20 or 25 miles would be a high plateau, arched a little along the central line, but otherwise remarkably even.

Upon first recognizing the existence of this uplifted and dissected plain, I attributed it to the original constructional surface, but a little reflection showed this to be untenable. The volcanic cones, craters, and other causes of unevenness in the original surface have disappeared over the cordilleran region. Even the Panama tuffs so well represented in the foot-hills on the south of the high sierra, and which must have lapped over onto this region, have been completely removed.

To my mind the most unanswerable argument in favor of the idea of great erosion over the Veraguas Mountain belt is in the fact that at places the syenite rises to the level of the old plain. This coarse crystalline certainly did not solidify at or very near the surface, but must have been buried under a considerable mass of other rocks. Moreover, the "higher" strata are absent on the north side of the mountains along the coast of the Caribbean Sea. On the whole, I consider the evidence of erosion over the cordilleran region to form the ancient plain of the sierra summits sufficiently strong to make it practically a demonstration.

Between the Aguadulce-Santiago plain and the high sierra is a belt of lower mountains or montañas, 10 to 20 miles in width. It is made up of separate ridges trending in various directions, and of isolated peaks. At first sight the whole seems to be an unsystematic collection of steep-sided and narrow-crested hills of various heights; but from certain advantageous points of view the impression is forced on the observer that if a plane were drawn from the edge of the dissected plateau over the cordillera to the summit plane of the monadnocks on the low plain, many of the summits of the foot-hills would fall in this plane *and none above it.* Where erosion has been very active in this belt, the ridges have been reduced below the old plain surface, but the bulkier ones with comparatively even crests, and the larger isolated peaks form a sloping, dissected plain almost as perfectly as do the monadnocks below.

That this plain does not represent the original constructional surface is demonstrated partly by the total disappearance of the cones and craters, but better yet by the fact that at many places among these montañas, the structural features are beautifully displayed, especially through the presence of thick, originally nearly horizontal lava sheets, now dipping steeply in the opposite direction from the slope of the supposed ancient plain which bevels their upturned edges. Indeed, the volcanic strata of the foot-hills north and west of Santiago have a prevailing northerly dip or toward the cordillera, only a part of which dip I think was original.

It has been shown above that there exists over the entire width of the Isthmus west of the head of the Bay of Parita (the Peninsula of Azuero possibly in part excepted), an uplifted, deformed and nearly destroyed ancient plain of erosion. In the comparatively short time in which, it is known, this plain was formed, it is impossible that it can have been the work of the sea. Marine erosion proceeds rapidly relatively to the land surface exposed to its action, but very little of it is acted on by the sea at one time. The construction of broad submarine shelves requires an extremely long time and a sinking coast with the accumulation off shore of thick sediments. In the light of recently acquired knowledge on the subject, I do not think it is necessary to indulge in any elaborate discussion to demonstrate that the leveling of the Isthmus was done by the ordinary agencies of sub-aerial erosion—that the now dissected plain was one of land surface denudation, or, in other words, a peneplain.

The age of the supposed upper peneplain may be roughly fixed by a study of the newest formation involved in the denudation and by a comparison of the erosion accomplished since the uplift of the peneplain with that of certain portions of the United States where physiographic studies are well advanced.

The newest formation under the plain seems to have been the alkaline granite and syenite batholites of the cordilleran region, of an age certainly newer than the Eocene and probably about middle Miocene. Some time was required for the removal of a considerable thickness of strata from over the crystallines, and this may throw the time of uplift of the peneplain forward to at least the late Miocene.

Over the Aguadulce-Santiago plain the uplift has been slight (50 to 500 feet) and the strata soft; hence, erosion here has proceeded to such an extent as to leave the original peneplain surface remaining only in widely separated tracts of exceedingly limited area. In the foot-hill region, the erosion of valleys from 1,000 to 2,500 feet in depth has carried away fully two-thirds of the strata between their bottoms and the old peneplain. In the cordilleran region, the old plateau is nearly thoroughly dissected by valleys several thousand feet in depth and of no mean width. The valleys in this Cordillera de Veraguas may be directly compared with those of the Black Hills of South Dakota, the deep cañons of the Sierra Nevada and Klamath Mountains of California, and certain deep but not broad valleys of the Appalachian region, as those of the West Virginia plateau. Taking into consideration the hard crystalline rock, but otherwise favorable conditions for rapid erosion, the valleys of the cordillera need not have required such a long period of erosion as the first and last of those in the United States mentioned above, although it is hardly possible that they could have been excavated solely within the Pleistocene era. I believe the evidence warrants our provisionally classing the uplift of the peneplain as an event of the Pliocene period.

The late Tertiary uplift was of the nature of a broad arching of the rocks with an east-west axis occupying the position of the present high sierra. The peneplain in the cordilleran region was not immediately raised to its present altitude of about 5,000 feet, for part of the uplift is due to movements as recent as the late Pleistocene.

The Pleistocene Peneplain.—When I first traveled over the beautiful grassy plain with island-like clumps of dark green arborescent vegetation, between Aguadulce and Santiago, I assumed without serious questioning that it is an old coastal plain of aggradation, and the isolated, often cone-shaped elevations on it, volcanic cones. But when I came to study the strata under it, I found, instead of the loose sands and clays of Pleistocene age that I had expected, conglomerates, breccias, shales and tuffs of Eocene and earlier age, the whole horizontal in a general way, but considered in detail always dipping perceptibly and often decidedly in some direction.

The plain everywhere bevels the edges of the slightly upturned strata.

Toward Aguadulce there are broad stretches of open grassy plain which are remarkably even but not flat; that is, they are characterized by long, extremely gentle even slopes which form shallow basins, in the deepest portions of which a few streams may be found in the rainy season. Farther west toward Santiago, the plain becomes more rolling and monadnocks more numerous. Because of an uplift the streams do not now flow on the peneplain, but have eroded beneath its surface valleys to as much as 100 feet in depth. On the inter-fluvial portions the original peneplain surface remains as grassy llanos, very slightly arched in the center and remarkable for their long, slight, even slopes. Low ranges of hills (residuals) traverse the plain in various directions and often isolated, rounded elevations are encountered.

Standing on the foot-hills of the cordillera and looking over the plain, it is seen to be a perfectly base-leveled area of denudation. The shallow basins, the low divides, and the cañon valleys disappear with distance and we see only a land apparently as flat as the ocean except for the many monadnocks which rise sharply from it. It is the most beautiful and perfectly base-leveled land with which I am acquainted.

The Pleistocene base-level is found at intervals along both coasts of the Isthmus and was recognized by Mr. Hill at Colon, in the truncated summits of the Monkey Hills, and at Panama, where it constitutes the terrace on which the city is mainly built. Mt. Aucon, which rises prominently just beyond the city, and most of the islands in the bay, were monadnocks or residuals on this peneplain. It was once developed over the area of the Gulf of Panama, but within its limits is now represented by a single remnant, a flat-topped island about 10 miles southwest of the city.

At the foot of the Cordillera de Veraguas on the northern or Caribbean side of the Isthmus, base-leveling was effected on the hard crystallines and andesite(?) of the Veraguas series over a belt at least several miles wide. This has since been uplifted and tilted toward the sea. The streams have eroded in the plain narrow cañon valleys from one to several hundred feet deep, but all the

ridges thus formed have an even and gentle slope toward the ocean. That they represent a plain of sub-aerial erosion is evident from the presence on the summits of many of them of gold-bearing river gravels, the remnants of old delta-like alluvial fans formed at the mouths of the mountain valleys.

The Pleistocene peneplain rises very gradually and evenly from about 25 feet above high tide level at Aguadulce to 370 feet at Santiago, a distance of 40 miles. From Santiago it has a more rapid slope to the head of the Gulf of Montijo, and in consequence it is deeply dissected and to a great extent destroyed in this region. Here is an excellent area for studying the question of its age, as it shows the maximum erosion. Cañon valleys from 100 to 200 feet deep and 100 feet to half a mile wide have been excavated by insignificant streamlets. Over areas as large as a township in the United States, the divides have been so generally reduced that it is difficult to detect any trace of the plain. Yet the altitude at which it is due is known from neighboring areas.

It is true that the slope, the softness of the formations, the absence of heavy vegetation, and the division of the year into one extremely dry and one extremely wet season, favor rapid erosion, but time is required to make a valley even on a precipitous mountain-side. Undoubtedly such a late age as the opening of the Recent period, the Wisconsin epoch or the Iowan epoch of United States geology, can not be entertained. It is doubtful even if all the erosion could have been accomplished since the opening of the Illinoian epoch. The Kansan epoch appears to have been too remote, and as for the Lafayette epoch, which closed the Pliocene history in the Eastern United States, it is out of the question. Considering the favoring conditions of erosion, I am averse to placing the uplift of the peneplain so far back as the early Pleistocene. So we will provisionally identify it as Middle Pleistocene in age.

PLEISTOCENE FORMATIONS.

There is in various parts of the Aguadulce-Santiago plain a bed of exceedingly finely divided clay which dries into coarse grains by the development of fine cracks. It is of a very light gray or

ashy color with brownish red spots due to iron staining. Stratification lines there are none unless very indistinct. There are no fossils, no hard iron concretions and no pebbles or other rock fragments. It is not residuary as it occurs over quite different formations without change of character.

This clay is overlaid conformably but with a sharp division, by a peculiar soft conglomerate of impure, light brown limonite pebbles, brown silt and clay, forming the surface formation in many parts of the plain. It is usually 6 to 8 inches thick except near waterways, where it increases to several feet. Often it is distinctly stratified and evidently waterlaid.

This ash-colored clay and the fine brown conglomerate are fresh-water deposits made at a time that the plain was low and liable to overflow from the sluggish streams. This was previous to the uplift of the plain and trenching of the present valleys and hence the deposits may be considered of Middle Pleistocene age.

In the town of Santiago, whose population is about 6,000, nearly one-third of the paving blocks are silicified wood. This was gathered from the plain in the vicinity where fragments of this material and even whole logs are widely scattered on the surface. North of Santiago, the plain over entire square miles has fragments of carnelian and agate very abundantly distributed in the soil. Numerous veins of quartz and chalcedony have been formed in the sub-soil within a few feet of the surface. This epoch of silicification preceded the uplift and dissection of the peneplain.

The Aguadulce Formation.—In the vicinity of the town of Aguadulce, the sea invaded the plain, leveled it off and deposited over the Panama formation a thick layer of gravel and sand which extends back several miles from the present seaward margin of the plain, but disappears so gradually that its actual original extent is hard to determine. There are a few low, broad beach ridges. The deposit is a mixture of more or less water-worn pebbles mostly local in origin, of coarse and fine sand, of clay and of limonite. The latter is the most important constituent and in places cements the gravel and sand into a dark reddish brown conglomerate or impregnates the clay so as to make it a veritable low-grade iron ore. Fragments of this impure limonite bestrew the surface and outcrop in large masses. It seems to indicate esturine conditions.

In this formation near Aguadulce are many small, smooth, subangular pieces of limonitic chert and hardened clay which have a peculiar semi-glazed surface and a uniform light brown color. A great number of these same water-worn brown pebbles are scattered over the plain far from the sea, particularly in the vicinity of the more important stream courses. They appear to be the river deposits of a certain age, as none were formed before or since. It is a singular fact that very similar pebbles of semi-glazed brown river gravel are widely distributed in the drift of northwestern Illinois, where I have described them under the name of "Freeport gravel," and they occur in southern Missouri and Arkansas, where I have traced them into connection with the Lafayette deposits. No suggestions of correlation are intended by this comparison.

The Aguadulce formation represents a slight local depression immediately preceding the uplift of the Pleistocene peneplain and may be classed as Middle Pleistocene.

The San Carlos Formation.—At many places on the Pacific side of the Isthmus are remnants of a coastal plain of aggradation which has been uplifted 20 to 100 feet above high tide level and partly destroyed by marine action. A beautiful example is the San Carlos plain, lying between 30 and 50 miles west-southwest of Panama, and extending from a 100-foot white sea-cliff inland probably five miles to the base of a mountain mass. Since its uplift, it has been dissected by narrow cañon valleys, but the inter-stream portions in general remain intact so that from a distance it looks like a remarkably level plain. The divides are flat instead of slightly arched as in the case of the Pleistocene peneplain. As might be expected, the sea-cliff shows that the plain is composed of a marine deposit of mainly horizontally stratified fine sand and beach gravel.

The sea-cliff about one mile east of San Carlos exposes the formation to perfection. In the maximum thickness of 100 feet there is included three divisions. At the base is a bed of very coarse gravel and boulders up to several tons in weight, which is well lithified and composed largely of the porphyritic and crystalline volcanic rocks of the Isthmus, in particular a red porphyry. It is of a dull brownish color. The surface is very irregular, rising from

below sea-level to about 50 feet above it. Some of it forms reefs at the outer edge of the beach at low tide.

The middle division is a false-bedded series of alternating layers of fine gravel and coarse sand. It has a greater variety of pebbles than that below and among the species represented are biotite granite and separate foils of biotite, a mineral very rare in the Isthmian country. Between the two gravel members, there is a sharp but irregular line which affords some evidence of two periods of deposition, separated by marine erosion.

The upper third of the cliff consists of heavily-bedded, horizontal, semi-lithified fine sand and silt of a light yellowish color with a tendency to buff. In some layers there is a large constituent of grains much finer than sand, so that these beds resemble loess.

So far as I have been able to learn, the San Carlos plain of aggradation is continuous, back of the immediate coastal lands, with the Aguadulce-Santiago plain of denudation. While base-leveling was in progress on the land along the coast, the eroded materials were deposited, as the San Carlos formation, in the sea just off-shore, and as fast as its surface rose to that of high tide level, its area was added to that of the land as a continuation of or appendage to the plain of denudation.

The rather small size of the cañon valleys eroded in the San Carlos formation since its elevation indicate an age rather late in the Pleistocene era. In quantitative terms, this erosion may be directly compared with the post-Illinoin erosion in the Mississippi basin and the erosion accomplished on the Red Bluff formation of the Sacramento Valley.

I wish to remark here that those who are not intimately acquainted with climatic conditions on the Isthmus of Panama, may be misled by statements of its supposed heavy annual precipitation, which is said to vary for different parts of the country from 100 to 250 inches per year. It will be natural to infer that the streams must be in a state of almost chronic flooding and erosion extremely active. Now, on the southern side of the Cordillera de Veraguas, where are situated the Pleistocene formations whose age I have endeavored roughly to determine by erosion studies, there is a comparatively dry belt, with six months in which scarcely a drop of rain falls,

and during the rainy season, the streams are not more flooded than those of the Sacramento Valley in the winter season. It is unwarranted to assume that erosion has been very much more active here than in the Mississippi Basin or the Sacramento Valley. This applies only to the comparatively dry belt above mentioned.

On the whole, I think we are justified in provisionally placing the San Carlos formation in the Middle Pleistocene.

The Mariato Formation.—On the eastern side of the Gulf of Montijo, about seven miles north of the mouth of the Torio River, there is a grassy and level but dissected old coastal plain, occupied by the hacienda of Mariato. It is elevated 20 to 40 feet above sea-level. On the seaward margin it has been much eroded, and at "the port" it is seen to be composed of horizontally stratified, reddish colored clay, which is very sandy above and gravelly below. The pebbles are well rounded, but mostly of soft rock which can be broken with the point of a knife. This marine deposit rests on an ancient submarine shelf carved from the Santiago formation, upon whose nearly flat surface it thins out in passing inland.

This Mariato coastal plain has the same relation to the neighboring mountains, to a low coastal plain of later age, and to the present rivers and bays, as the San Carlos Plain. Lithologically, the Mariato formation is much like the Red Bluff in California (which means little), and it has been eroded to about the same extent as the latter under approximately similar conditions, which is significant.

THE MIDDLE PLEISTOCENE UPLIFT.

If all the fragmentary coastal plains, the Pleistocene peneplain on the Pacific side of the Isthmus, and the base-level on the Caribbean side at the foot of the Cordillera de Veraguas, were uplifted at the same time, as the evidence indicates, we have a definite and perhaps important orographic disturbance in the middle part of the Pleistocene era. This was not a mere epeirogenic uplift, without deformation, of the entire Isthmus, but a broad arching of the country in a system outlined in previous disturbances. The actual amount of uplift along the line of the present shores was quite

insignificant, a little more than 100 feet at San Carlos probably being the maximum. The plains were tilted toward the seas on both sides of the Cordillera de Veraguas, and from the angles at which they slope it is probable that along the axis of the cordilleran region, the land rose as much as several thousand feet. In traversing that region, even before recognizing the significance of the tilted plains, I was satisfied that the sierra had suffered a considerable uplift in comparatively recent times. I now know that the whole region has been bowed. Some of this arching may be due to a recent movement perhaps not yet ended, but a considerable part dates from this Middle Pleistocene disturbance.

On the western side of the Peninsula of Azuero, south of the tilted Mariato coastal plain, the Pleistocene peneplain was developed on hard formations, but it has been uplifted and cañoned by the streams. It rises inland at such a rate as to indicate that the central line or mountain axis of the peninsula has risen since Middle Pleistocene time as much as 1,000 or more feet.

A RECENT DEPRESSION OF THE COASTAL LANDS.

The outline of the Isthmus of Panama is that of a land whose borders have recently subsided and been partially submerged. Especially is this true of the Pacific side. West of the Peninsula of Azuero are several beautiful examples of drowned valleys. That of Montijo begins far inland as a common river valley of the cañon type, and an age subsequent to the uplift of the Pleistocene peneplain. As it proceeds southward it opens up into a broad topographic depression partly of structural and partly of erosive origin. Tide water ascends in this to 40 miles from the open ocean, and the body of water gradually widens until it is several miles in width and has become the so-called Gulf of Montijo, partly closed in from the open sea by several large islands. The "gulf" is shallow and in its upper portion great mud-flats are exposed at low tide. Evidently the depression which admitted the sea into the old valley had a very small amplitude.

Around the extremity of the Peninsula of Azuero, the evidences of a recent subsidence are very clear. It always seems that the depression has been most on the ends of long headlands and relatively

slight at the heads of deep bays. This seems to point to a slight tilting of the interior toward the sea. Indeed, I am not certain that the real nature of the movement was not a slight arching of the Isthmus as in previous periods of disturbance. Away from the coastal lands, especially in the high mountains, I found, instead of traces of a recent subsidence, rather strong evidences of an uplift which was probably contemporaneous with the submergence of the coasts.

The geologically very recent age of the depression is exemplified by the small amount of marine erosion which has been effected on the precipitous headlands and mountainous islands. As Mr. Hill has mentioned, the cliffs of marine erosion are only from 20 to 100 feet in height, and above them the land presents the type of topography indicative of slow subaerial erosion. Since the coast line reached its present position on the land slopes, the bench cut by the waves is insignificant, comparatively speaking, and can not have required a very long time. A movement and consequent shifting of the shore-lines has certainly occurred recently. It was not one of uplift of the land, for there are no raised shore lines. Wave-cut benches above the present shore line (the single marine shelf of the Middle Pleistocene base-level excepted) are totally absent from the Isthmian country. As indicated by various phenomena, the recent movement has been one of subsidence on the coasts.

The Parita Formation.—Around the head of shallow, sheltered bays, there have been built up, since the subsidence, low coastal plains, sometimes of considerable extent, even several miles in width. The best developed is at the head of the Bay of Parita. It consists of dark bluish gray silty muck and gray sand. This has been built up to a level mainly a few inches above that of high tide, although on the inland borders there are extensive tracts which are flooded at spring tide, as at the Aguadulce Salt Works. The plain is traversed by deep, narrow tidal channels.

These flats must have required a considerable period for their formation, and during it the coast-line has been remarkably permanent. They are connected with low alluvial bottoms of small extent along some of the rivers which enter the sea through the

coastal flats, and which correspond to the alluvial plains of Modern age along nearly all our rivers in the United States.

Modern Stream Gravels.—Along many of the streams of the Isthmus there are beds of large boulders, coarse gravel and sand, which form terraces or elevated alluvial plains, not nearly as high as the ancient river gravels on the Aguadulce-Santiago plain, but still for the most part out of the reach of the present streams. They are the gold-bearing gravels. They seem to indicate a slight uplift of the land in a time very recent. It is this elevation of the interior which I correlate in a general way with the recent subsidence of the coastal regions and consider both to have occurred at about the opening of the Modern or present epoch of the Pleistocene era.

SUMMARY OF POST-EOCENE EARTH MOVEMENTS.

The disturbances of the level of the land on the Isthmus of Panama, since the Eocene period, may be summarized as follows:

1. A marked elevation supposably at about the middle of the Miocene period.

(*a*) A long quiescent period resulting in the formation of the Tertiary peneplain.

2. Another marked uplift, inferentially in some part of the Pliocene period.

(*b*) Erosion of deep valleys in the mountains and formation of Pleistocene peneplain.

3. An uplift near the middle of the Pleistocene period. Insignificant in amount on coasts as compared with previous uplifts.

(*c*) Excavation of cañon valleys in uplifted coastal plains and deepening of cordilleran valleys.

4. An extended but slight submergence of coastal lands near the opening of the Modern epoch, with probable correlative elevation inland.

(*d*) Formation of low coastal plains on the Pacific side and coral reefs on the Caribbean side of the Isthmus, as at Colon.

ORIGIN OF ISTHMIAN STREAM COURSES.

The courses of nearly all the streams of the central portion of the Isthmus of Panama are governed primarily by the general slope of the dissected peneplains. They rise at the axes of the great structural arches and flow directly down the slopes of the tilted peneplains into the sea. Several small streams in the foothills north of Santiago may be exceptions, as their courses seem to have been determined in part by the northwest to southeast strike of the strata, but, in general, I believe the drainage to be independent of the rock structure. Certainly there has been a radical readjustment since the Eocene volcanic period, and this seems to have been accomplished mainly during the inception of uplift of the Tertiary peneplain. The stream courses seem to have been brought under some straightening process which may have been the rapidity of tilting of the peneplain.

In the Montijo basin the drainage has been reversed through the elevation of the Cordillera de Veraguas and the submergence of the "old land" on the south. Most of the rivers on the western side of the Peninsula of Azuero flow down out of the mountains toward the northwest and they may be relics of the drainage system in the basin before the reversal. Just when that occurred I could not determine.

PLEISTOCENE OSCILLATIONS OF THE SOUTHWEST COAST OF NORTH AMERICA.

The same evidences of a geologically very recent depression of the coastal lands are found all along the Pacific side of the continent as far north as the Bay of San Francisco. Prof. A. C. Lawson* and Dr. H. W. Fairbanks† have recently discussed the subsidence on the Californian coast. Here the recent submergence appears to have been rather local in character. The late Pliocene and early Pleistocene submergence of the southern California coast, marked by raised shore-lines, did not extend as far as the Isthmus of Panama, and I hardly think was represented on the coast of southern Mexico and Central America.

*Bulletin of the Department of Geology, University of California, Vol. I, No. 4, December, 1893.

†American Geologist, Vol. XX, No. 4, October, 1897.

The city of Mazatlan, Mexico, is situated on a short drowned valley. From here southward, the ocean is mainly bordered by mountains, the bases of many of which rise directly from the sea. At San Blas there is a representative of the low coastal plains of Modern age, formed since the depression. The beautiful land-locked harbor of Acapulco is another instance of a short deep valley converted into a bay through the subsidence of the coast.

From Cape Corrientes to Salina Cruz, close to the Guatemala line, the coast is very precipitous and mountainous. Then there is a radical change, for the mountains trend off to the east into the interior, and across Guatemala, a broad low coastal plain lies next the Pacific. This may be as much as 15 miles or more in width and is backed by a high volcanic range, including the famous "Volcano of Water" and the "Volcano of Fire," near the city of New Gautemala. These volcanoes are of quite recent formation, and their topography is markedly different from that of the greater part of Mexican and Central American Mountain Ranges. While sailing along the coast between San Francisco and Panama, I distinguished two principal types of mountain ranges. One is characterized by distinct erosion topography, with sharp, rocky peaks, deep valleys and numerous ravines. Most of the mountains seen from the sea even in Central America are of this class. It is the only one represented, except as to the peak of Chiriqui, on the Isthmus of Panama.

The other type is characterized by high, cone-shaped peaks, remarkable for their long, slightly curved, but even slopes. The smoothness of the topography in strong contrast to the roughness of the other type, will appeal even to the unscientific observer as indicating an extremely recent age.

The low coastal plain of Gautemala extends to Acajutla in San Salvador, where it has been bowed up about 40 feet by a slight disturbance perhaps connected with the active volcano seen near by. The sea has eroded a low cliff into the arched strata and revealed a harder formation under the light-colored sand of which the low coastal plain is largely composed. This lower formation I believe to belong to another coastal plain which was largely submerged and the present low coastal plain built on it.

South of Acajutla, the low coastal plain is represented, but at and near La Libertad, in San Salvador, the land next the coast is an elevated plain, much dissected by cañon valleys and remarkably like an uplifted and dissected Pleistocene peneplain. It rises rapidly to the foot of the mountains several miles distant inland. South of here the immediate coastal lands consist chiefly of the low plain, especially along the coast of Nicaragua. At Corinto, a low, narrow ridge of reddish colored stratified rock like sandstone forms a rim outside of the low, coastal plain, which latter is miles in width and traversed by broad crooked estuaries or salt-water channels so common in the low coastal plain region. The sandstone ridge at Corinto seems to be a remnant of another coastal plain now largely submerged and the present low coastal plain built on it.

It is evident to me that from the Isthmus of Tehuantepec to the mainland of South America, the Pacific coast has had the same history. During the Pleistocene era there have been two coastal plains formed. The first or Middle Pleistocene plain was mainly one of erosion inland and aggradation on the seaward border, and was more extensive than the present coastal plain. Then there was a tilting of this plain toward the sea, with local variations of the disturbance. As a general thing the plain was elevated, and dissected by stream erosion inland and largely destroyed by marine erosion on the seaward margin. About at the close of the Pleistocene period, a movement of depression submerged the seaward portion, forming islands from some of the isolated low mountain masses which formerly stood as monadnocks on the plain. Subsequently the sea built another coastal plain over the portions of the old plain which were but slightly submerged.

The subsidence of the Pacific coast of Central America and the Isthmus of Panama was very slight, probably nowhere amounting to as much as several hundred feet. On the Mexican coast and farther north it seems to have been greater in general but more local in character. The occurrence of such a slight subsidence in the Recent period along over 3,000 miles of coast is remarkable, and indicates that the disturbance was one of a continental nature.

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A CONTRIBUTION

TO THE

GEOLOGY OF THE JOHN DAY BASIN

BY

JOHN C. MERRIAM

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INTRODUCTION.

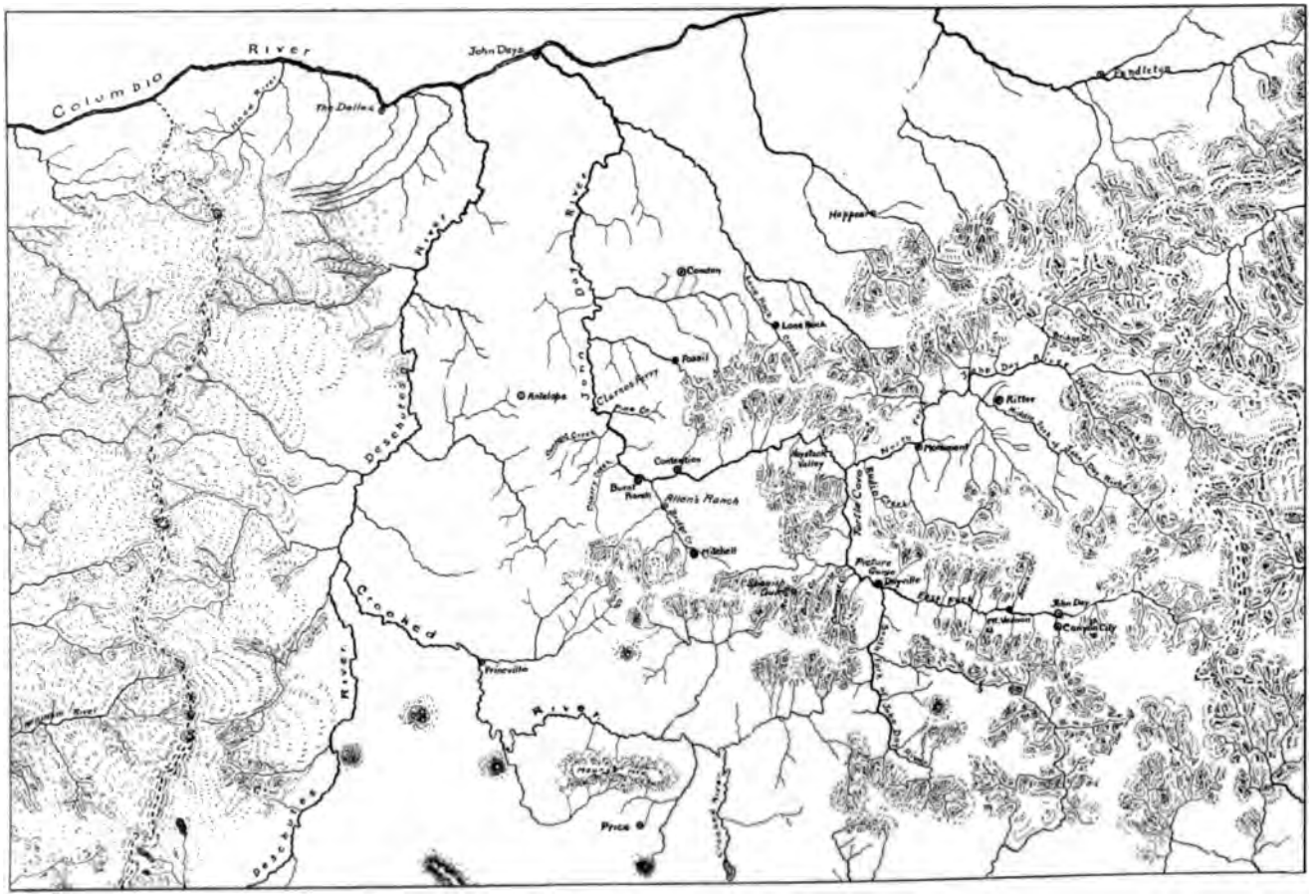
During the summer seasons of 1899 and 1900, the writer traveled over a considerable part of the John Day basin, while in charge of palæontological expeditions sent out from the University of California to collect vertebrate fossils. The following discussion of the geology contains the results of observations made while engaged in that work.

Though the object of the expeditions was the acquisition of specimens, much of the value of the material being dependent on the circumstances of its occurrence, efforts were made from the beginning to determine, as accurately as possible, the stratigraphic relations of the fossil-bearing beds.

In looking over the literature bearing upon John Day geology, before visiting the field, the writer was considerably surprised to find that only a few short paragraphs relating to the subject had ever been published, and that in many of the most important particulars these accounts were decidedly contradictory.

In view of the disagreement among observers regarding the geological history of the region, it was perhaps to be expected that no single account would be found to agree with the facts. The first season's work in the field demonstrated that this was actually the case, and showed the necessity of working out the true stratigraphic succession as an indispensable preliminary to satisfactory palæontological work. With this object in view, as much information was gathered as could be obtained without interfering seriously with the main work of the expeditions.

Future investigations will certainly show that very many important things have been overlooked, and doubtless many weaknesses in the present discussion will be pointed out; the writer's purpose will, however, be accomplished if the general stratigraphic succession and the sequence of major geological events are here set forth in such a manner as to make intelligible discussions of the


Columbia River
The Dalles
John Day
Deschutes River
Crooked River
Prineville
Antelope
Clarno's Ferry
Post Office
Camp Creek
Cantonment
Burnt Ranch
Allen's Ranch
Mitchell
Lone Rock
Fossil
Canyon City
Monument
Ritter
Picture Gorge
Dayville
Prairie Creek
Bridge Creek
Price
Hoppes
Haystack Valley

extinct faunas and floras of this region which will follow this paper.

The writer is indebted to Mr. F. C. Calkins for all petrographical determinations mentioned in this paper. Mr. Calkins has now in preparation an article on the rocks of the John Day region.

Mr. V. C. Osmont has contributed some valuable information concerning the geology of the region south of the Blue Mountains.

To Dr. T. W. Stanton the writer is under obligation for the contribution of a note on the Cretaceous fossils collected at Spanish Gulch.

Prof. T. H. Knowlton has kindly undertaken the study of the fossil plants obtained by the University expeditions, and furnishes for the paper tentative lists of species with a brief discussion of the affinities of the floras. In a bulletin of the U. S. Geological Survey, which is now in preparation, Professor Knowlton will present a discussion of the John Day floras based on a study of all of the collections which have been obtained from that region.

GEOGRAPHIC FEATURES.

The existing John Day basin of north central Oregon is a well-defined area almost completely surrounded by the triangular Blue Mountain Range. The rugged eastern ridges, rising to an elevation of over 6,000 feet, are composed largely of pre-Tertiary formations which have been much disturbed. To the west the ranges are made up principally of Tertiary lavas forming regular and frequently flat-topped ridges somewhat lower than those to the east.

Inside the basin are a number of smaller ridges and plateaus, among which the John Day and its tributaries wind in deep and often narrow cañons. The streams have here laid bare magnificent sections of all the basin formations, affording unexcelled opportunities for stratigraphic and palæontologic studies.

The main John Day River leaves the west side of the basin through a gap between the north and south ranges of the Blue Mountains. From this point it flows approximately north to the Columbia. Tracing the river back from the gap, its course is seen to be nearly east, till, at the lower end of Turtle Cove, it is divided into two streams, known as the North Fork and the main river

As the North Fork is the larger stream, the writer has fallen into the habit of calling the southern branch the South Fork. At Dayville the South Fork divides into two streams, of which the southern is known as the South Fork and the other as the main river. To avoid confusion the writer will refer to the northern branch here as the East Fork. The course of the South Fork from Dayville is across the southern range, to the south of which it occupies a small basin which the writer has not visited.

Excepting the mountain ranges and some of the highest interior ridges, which support a heavy growth of pine timber, the country is only sparingly wooded. A fringe of cottonwoods, birches, and willows along the streams, and a few scattered junipers comprise the most important part of its sylva. The basin is mainly an open grass country with a sprinkling of sagebrush on the bottom-lands. Some years ago a rich growth of bunchgrass over a large part of the area supported large herds of cattle. Latterly the sheep industry has overshadowed all others and the grass has been rapidly disappearing.

HISTORY OF EXPLORATION.*

The existence of fossil mammalian remains in Eastern Oregon seems to have been first noticed by a company of soldiers which passed through that region in 1861. When the party reached The Dalles on its return journey, a number of the men had with them fragments of bones and teeth obtained from fossil beds in the Crooked River country. The only specimen brought back by this party, of which any definite information is now obtainable, was a fine rhinoceros jaw, which was in the possession of Lieutenant Waymire.

Prof. Thomas Condon, who was then pastor of the Congregational Church in The Dalles, saw the fossils and obtained from the members of the party considerable information concerning their

*The writer is indebted to Prof. Thomas Condon for the greater part of his information concerning the discovery of the fields. Mr. L. S. Davis, who has accompanied nearly all of the expeditions, contributed most of the facts concerning the later exploration.

occurrence. Condon immediately concluded that an important field for palæontological research had been discovered and made use of the first possible opportunity of visiting the beds. Early in the next year he was allowed to go with a company of soldiers taking supplies across to Harney Valley. On the road out, he passed through the Crooked River country and obtained a few fossils there. On the return trip, made by the way of Camp Watson, he discovered the large exposures at Bridge Creek and supposed them to be of the same system as the Crooked River beds.

In passing through the John Day country on his return journey, Condon met Sam Snook, a resident of the region who had already taken some notice of the fossil bones, and engaged his service as a collector.

The following summer, 1863, found Condon again collecting and exploring at Bridge Creek and along the John Day.

In 1864, probably in company with Snook, he first saw the large exposures of John Day strata in what he has named Turtle Cove.

In 1870 or '71, some specimens of teeth from the John Day beds were sent by Condon to Prof. O. C. Marsh. Almost immediately he received a request from Marsh to guide an expedition from Yale into the new field. Marsh came out with a party of fifteen or sixteen persons in the fall of 1871, and under Condon's guidance visited some of the most important localities. A small amount of collecting was done in what are now known as the John Day and Mascall beds, but the work was chiefly reconnaisance. While in the field Marsh engaged several collectors to carry on the work for him. Systematic collecting began in the following spring and was continued practically without interruption till 1877. Most of the work during this period was done by L. S. Davis and William Day, wno explored practically all of the exposures in the region.

Early in the winter of 1871, shortly after Marsh's visit to the field, Lord Walsingham, William de Gray, while on a hunting expedition, passed through the fossil fields and obtained some valuable specimens at Turtle Cove and on Bridge Creek. His small collection was presented to the British Museum and furnished

material for Bettany's* valuable contribution to our knowledge of the John Day Oreodontidæ.

In the summer of 1873, Prof. Joseph Le Conte,† in company with Professor Condon, visited the western border of the field and made some important observations on the geology.

Parties under Wortman and Sternberg collected for Prof. E. D. Cope in 1878 and 1879, obtaining the material upon which Cope based his important publications on John Day vertebrates.

In the summer of 1880, Captain Bendire, of the U. S. Army, with a large party of the 7th U. S. Cavalry, made a short tour through the basin under the guidance of L. S. Davis. Collections of plants were made by him at Bridge Creek, Van Horn's Ranch, and probably also at Cherry Creek. A few fish remains were collected in the plant beds at Van Horn's Ranch and small collections of mammalian material were obtained at several localities in the John Day and the Mascall formations. Through some unfortunate mistake, Bendire's collection of plants and fish from the Mascall seems to have been considered as coming from below the John Day, and dire confusion has been the result of all geological publication based upon that supposition. Bendire's collections were turned over to the Smithsonian Institution. The plants were afterwards described by Lesquereau,‡ and the fish by Cope.§

In 1882, Davis and Day collected under Marsh for the U. S. Geological Survey. Their work seems to have been confined to the beds south of the Blue Mountains.

No farther work was done in the field till 1889, when Prof. W. B. Scott spent the summer in the John Day basin with a large party from Princeton University. After Professor Scott's return a portion of his party worked over the country south of the mountains.

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*G. T. Bettany. On the Genus *Merycochœrus*, Quar. Jour. Geol. Soc. Lond., 1876, V. 32, p. 259.

†Am. J. Sc., 1874, Vol. 7, p. 167.

‡Proc. U. S. Nat. Ins., 1888, pp. 13-19.

§Am. Nat., 1889, p. 625.

LITERATURE.

The first mention of the fossiliferous deposits in the John Day basin which appears in the literature was made by Dr. Joseph Leidy. In October, 1870, Leidy presented before the Philadelphia Academy of Sciences* a short paper, in which he described "a collection of fossils recently received for examination through the Smithsonian Institution, from Rev. Thomas Condon, of Dalles City, Oregon." The collection consisted of "remains of mammalia obtained by Mr. Condon from the valley of Bridge Creek" (and "Big Bottom of John Day"), "a tributary of John Day's River, Oregon." The collection included new forms of *Paracotylops* (*Merycochœrus*), *Rhinoceros*, and *Anchitherium*. New occurrences of *Agriochœrus*, *Leptomeryx*, *Lophiodon* (?), *Elotherum*, and a Dicotyles-like form were also noted. Most of the previously-known species, as identified by Leidy, were forms belonging to the White River fauna, and he probably considered the John Day beds as of nearly the same age as the White River.

In 1873 Professor Marsh described† several new fossil mammals obtained by his exploring party in the John Day country in 1871. He referred two forms to the Miocene and one to the Pliocene, thus making the first statement regarding the age of the beds.

In his paper on the great lava flood of the West, Prof. Joseph Le Conte‡ makes the first mention of the structural relations of the John Day formations. His statement regarding the relation of the lava to the John Day beds is in part as follows: "The lava in this region is * * * underlaid by the remarkable fossiliferous Miocene lake deposit of the John Day Valley; erosion has cut through the lava cap into the soft strata beneath."

The earliest general discussion of John Day geology which appears in the literature is the following statement published by Marsh§ in 1875.

"The Blue Mountains formed the eastern and southern shores of this lake, but its other limits are difficult to ascertain, as this

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*Proc. Phil. Acad., 1870, p. 112.

†Am. Jour. Sc., 3d ser., V. 5, p. 409.

‡Am. J. Sc., 1874, V. 7, 3d ser., p. 167.

§Am. J. Sc., 1875, Ser. III, Vol. 9, p. 52.

whole country has since been deeply buried by successive overflows of volcanic rock. It is only where the latter have been washed away that the lake deposits can be examined. The discovery and first explorations in this basin were made by Rev. Thomas Condon, the present state geologist of Oregon. The typical localities of this Miocene basin are along the John Day River, and this name may very properly be used to designate the lake basin. The strata in this basin are more or less inclined and of great thickness. One section near the John Day River, examined by the writer in 1871 and again in 1873, seems to indicate a thickness of not less than 5,000 feet. The upper beds alone of this series correspond to the deposits in the White River basin. The lower portion also is clearly Miocene, as shown by its vertebrate fauna, which differs in many respects from that above. Beneath these strata are seen, at a few localities, the Eocene beds containing fossil plants mentioned above. They are more highly inclined than the Miocene beds, and some of them show that they have been subjected to heat. The inferior strata elsewhere are Mesozoic, and apparently Cretaceous. Above the Miocene strata Pliocene beds are seen in a few places, but basalt covers nearly all."

In this account we find the name "John Day" first used for the principal fossil beds of the basin. The relation of this horizon to the great lava beds is also correctly stated, though it is not quite clear whether he considered the Pliocene as also covered by the basalt flows. The Pliocene referred to is pretty certainly the Mascall beds. It is known that Marsh camped near the typical exposure of this formation and did some collecting in it. To what Marsh referred in his statement concerning Eocene and Cretaceous it is not certain. He has, however, correctly described the stratigraphic sequence.

In 1880 Prof. E. D. Cope* published the following statement concerning the geology of the John Day country:—

"The regions of the John Day River and Blue Mountains furnish sections of the formations of central Oregon. Above the Loup Fork or Upper Miocene there is a lava outflow, which has

*Cope Proc. Am. Phil. Soc., 1880, p. 61.

furnished the materials of a later lacustrine formation, which contains many vegetable remains. The material is coarse, and sometimes gravelly, and it is found on the Columbia River, and I think also in the interior basin. Professor Condon, in his unpublished notes, calls this the Dalles Group. It is in turn overlaid by the beds of the second great volcanic outflow. Below the Loup Fork follows the Truckee Group, so rich in extinct mammalia, and below this a formation of shales. These are composed of fine material, and vary in color from a white to a pale brown and reddish-brown. They contain vegetable remains in excellent preservation, and undeterminable fishes. The *Taxodium* nearly resembles that from the shales at Osino, Nevada, and on various grounds I suspect that these beds form a part of the 'Amyzon Group' (American Naturalist, June, 1880), with the shales of Osino and of the South Park of Colorado. Below these, is a system of fine-grained, sometimes shaly, rocks of delicate gray, buff, and greenish colors, containing calamites, which Professor Condon calls the *Calamite* beds. Their age is undetermined."

In spite of Cope's assumption that the plant and fish-bearing beds mentioned by him were to be correlated with his Amyzon* group, Lesquereau† referred the collections from Van Horn's Ranch to the late Miocene. In a later statement regarding the John Day stratigraphy‡, Cope speaks of the calamite beds as doubtless belonging to the Triassic or Jurassic. This horizon was determined by Lesquereau as Eocene.

In a recent bulletin by W. D. Matthew§ on a provisional classification of the fresh-water Tertiary of the West, there appears the statement that the Mascall formation (Cottonwood beds) is separated from the lower beds (John Day) by a basaltic flow. The loose gravels above the Mascall are also separated as a definite horizon.

In 1898 Wortman proposed the division of the John Day beds

*E. D. Cope, Am. Nat., 1879, p. 332. Late Eocene or Early Miocene, Nevada.

†Proc. U. S. Nat. Mus., 1888, p. 13.

‡Hayden Surv. Terrs., Vol. 3, p. 16.

§Bull. Am. Mus. Nat. Hist., V. 12, p. 19, 1899.

into the upper or Merycochoerus beds and the lower or Diceratherium beds.

GENERAL FEATURES OF THE GEOLOGY.

The section of the John Day formation, as it is known to the writer, includes at least nine formations, showing the following sequence:—

River terraces, with undisturbed Quaternary fossils.
Rattlesnake formation. Gravels, ash, tuff, and rhyolitic lava.
Mascall formation. Ashes, tuffs, and possibly gravels.
Columbia lava. Basaltic flows.
John Day series. Ashes, tuffs, and rhyolite flows. Sands and gravels near the top. Lower, middle, and upper divisions.
Clarno formation. Ashes, tuffs, andesitic and rhyolitic lavas.
Chico formation. Sandstones and conglomerates.
Knoxville formation. Black shales.
Pre-Cretaceous sedimentaries, serpentines. Granitic masses of unknown age.

The Knoxville and Chico are marine formations. It is not improbable that some of the eruptives below the Cretaceous have been intruded into it, though some of them are pretty certainly older than the Knoxville. From the Clarno formation to the top of the series, excepting a very small portion of the whole thickness, the deposits are made up of eruptive materials. The Clarno, John Day, and Mascall are almost entirely composed of ashes and tuffs. They have generally been considered as being wholly lake deposit, but, as will be shown later, the character and occurrence of the fossil remains which they contain are such as to make it doubtful whether they owe their origin solely to this mode of accumulation.

The Rattlesnake deposits also contain a large proportion of erupted material, but it is mainly composed of gravels derived from the Columbia lava.

At the close of a long era of erosion following the Rattlesnake epoch, a series of terraces was formed along the main streams. Undisturbed Quaternary remains give definite evidence regarding the age of these deposits.

The surface formation over the greater part of the basin is the Columbia lava, which has covered the whole region from the Cascades to the eastern Blue Mountain ranges. At points where the writer has been able to examine them, the existing northern and southern ranges are capped with a considerable thickness of Columbia lava. Ridges may, however, have existed in this region as early at least as the beginning of the Miocene, since the John Day deposits are either absent or much thinner along the existing ranges.

The Mascall beds are exposed principally in the southern part of the basin and south of the Blue Mountains. They are usually covered by a considerable thickness of Rattlesnake beds in which a rhyolite flow has been the main protection against erosion. The Rattlesnake beds are also confined, so far as the writer is acquainted with them, to the southern region. Exposures of the John Day beds and other pre-Columbia lava formations are found only along the streams, where the lava has been cut through.

PRE-CRETACEOUS FORMATIONS.

The oldest fossil-bearing strata which have been found in the John Day basin north of the southern Blue Mountain range are of Cretaceous age. At several points in the basin formations have, however, been found which have the appearance of being much older than the Cretaceous beds.

In the northeastern part of the basin a considerable area of quartz diorite is exposed on the Middle Fork, about five miles above Ritter. Where it was crossed by the writer, it is bordered by sedimentary rocks which show a degree of induration and deformation not met with in the Certaceous where it has been seen in the basin. On Desolation Creek to the northeast of the diorite area, this series seems to be extensively developed, and would, doubtless, repay careful study.

Opposite the Powell place, four or five miles above Ritter, on Middle Fork, fossiliferous middle Tertiary beds rest upon the older series. Columbia lava here covers the fossil beds and also laps over upon the diorite, from which it is separated by only a thin bed of ash.

At Spanish Gulch, twelve miles southwest of Dayville, the Chico Cretaceous is seen resting upon serpentine, which has the appearance of being intruded into it. At the head of the gulch the serpentine is separated from what was taken to be Chico conglomerate by a zone of schist and quartzite. Not far from this locality there is associated with the serpentine a considerable thickness of quartzite with quartz veins, which have produced some gold. Limestones quite different from any seen in the Chico are also exposed here. From the same neighborhood the writer obtained a specimen of a granitic rock, said to form one wall of a tunnel.

Though no direct proof can be presented, it seems probable that some of the rocks associated with the serpentine at Spanish Gulch are older than the Cretaceous.

At the junction of Muddy and Currant Creeks, six miles south of Clarno's Ferry, there are exposed several hundred feet of black slates showing a dip of about 20° to the northeast. At the mouth of Muddy Creek the cleavage of the slates runs almost east and west across the obscure bedding of the formation. On several occasions as parties have been passing through the region, search has been made in these beds for fossils, but so far no traces of them have been found. Judging from the appearance of this formation, it is older than the Knoxville shales.

Near the head of the Crooked River, south of the Blue Mountains, there are said to be exposures of Palæozoic, Triassic, Jurassic, and Cretaceous formations.

CRETACEOUS, CHICO AND KNOXVILLE.

Exposures of Cretaceous formations are to be found at several points on the western side of the basin. The best outcrops are seen at Mitchell and Spanish Gulch. At Spanish Gulch a considerable thickness of conglomerate and sandstone, dipping about 30° to the southwest, is found above the serpentine. Fossils are quite numerous in this formation, and considerable collections were made at two localities. All the material obtained was placed in the hands of Dr. T. W. Stanton, who has kindly furnished the following report:—

"The fossils come from two localities at Spanish Gulch, and only about three-fourths of a mile apart. The larger part of the

collection is from locality 814, well up on mountain at Spanish Gulch, Dp. 27° S. of W. This lot contains the following species:—

Anomia sp.
Mytilus sp. cf. *M. lanceolatus* Sowerby.
Trigonia leana Gabb.
Trigonia evansana Meek.
Meekia radiata Gabb?
Nucula (*Acila*) *truncata* Gabb.
Meretrix varians Gabb.
Meretrix sp. a.
Tellina ashburneri Gabb.
Tellina skidegatensis Whiteaves.
Asaphis multicostata Gabb.
Homomya concentrica Gabb?
Mactra? sp. a.
Corbula traskii Gabb.
Dentalium stramineum Gabb.
Gyrodes expansa Gabb.
Cinulia? sp.
Desmoceras dawsoni Whiteaves?

"Locality 813, west of locality 814 about three-fourths of a mile and probably higher in the section, yielded the following forms:—

Anomia sp.
Trigonia evansana Meek.
Chamidæ gen. et sp. ind.
Meretrix varians Gabb.
Meretrix? sp. b.
Tellina ashburneri Gabb.
Mactra? sp. b.
Corbula traskii Gabb.
Dentalium sp.
Scalaria clementina (Michelin)?
Solarium? sp.

"From the number of species in common it is evident that the fossils from the two localities belong to the same general fauna, though there might be some difference in horizon as their field rela-

tions seem to indicate. *Trigonia evansana*, *Meretrix varians*, and *Corbula traskii* apparently range throughout the Chico beds.

"A few of the names in the above list deserve a word of special comment.

"*Mytilus* cf. *lanceolatus* Sowerby. Represented by a single small specimen that seems to be identical with form from Skidegate Inlet, Queen Charlotte Islands, doubtfully referred by Whiteaves to *M. lanceolatus*. It also occurs at Texas Springs, California, and Jacksonville, Oregon.

"*Trigonia leana* Gabb. This is the species figured by Gabb in Paleontology of California as *T. gibboniana* Lea. He afterward considered it a new species and named it *T. leana*, but there is still reason to doubt whether it is really distinct from *T. tryoniana* Gabb which was described from an imperfect specimen that had lost the outer layer of shell. Some of the shells in the present collection have lost the outer layer of shell and thus acquired such a different aspect that they were at first considered a different species. *T. leana* occurs in the lower Chico beds at Jacksonville, Crooked River, Grave Creek, and other localities in Oregon, and at many places in California, including Texas Springs and Horsetown. The fossils from Skidegate Inlet, listed by Whiteaves as "*T. tryoniana?*" probably belong to *T. leana*, if it is really distinct from the typical *T. tryoniana*. If not, the latter name has priority, and should be used for the species.

"*Meekia radiata* Gabb? This species is represented by a number of well-preserved specimens differing materially from the figures of Gabb's type in that they attain a much larger size, being as large as *M. sella* Gabb, and have the whole surface covered with radiating sculpture. Specimens of smaller size but with precisely similar sculpture have been collected at Texas Springs, California, and the same form occurs at Grave Creek, Oregon, associated with others in which the surface is partly exfoliated and the radiating sculpture is very obscure. These facts lead to the suspicion that *M. radiata* was based on the miniature or depauperate specimens, in which the surface was not perfectly preserved, and I have, therefore, not ventured to separate these larger well-preserved specimens as a distinct species.

"*Chamidæ.* There are several small fragments apparently belonging to an undetermined genus] of Chamidæ, showing a structure similar to *Coralliochama*, but not identical with it.

"*Meretrix varians* Gabb. This variable species is widely distributed in the Chico. Whiteaves cites from Vancouver Island, under the name *Cytherea nitida* Gabb.

"*Tellina skidegatensis* Whiteaves. The collection contains a number of specimens referable to this species which was described from Bearskin Bay, Skidegate Inlet, Queen Charlotte Islands.

"*Asaphis multicostata* Gabb. This species, originally described from Crooked River, Oregon, is represented by a single imprint. *Linearia suciensis* Whiteaves is similar in form and sculpture and may be based on the same species.

"*Homomya concentrica* Gabb. The specimen in the collection is much larger than Gabb's figure and differs somewhat in form, but it is probably like the large specimens which he doubtfully referred to the species, and like those cited from the Sucia Island by Whiteaves. It is certainly identical with a form in the Geological Survey collection from Texas Springs, California.

"*Scalaria clementina* (Michelin)? The single fragmentary specimen appears to be identical in form and sculpture with the Queen Charlotte Islands species that Whiteaves* has listed under this name, and earlier figured as *S. albensis(?)* The same form occurs at Texas Springs.

"*Desmoceras* (*Puzozia*) *dawsoni* Whiteaves. A single fragment of an Ammonite in the collection agrees very well with the figures of this species from Queen Charlotte Islands formerly referred to *Haploceras beudanti* but recently named as above.†

"The whole assemblage of forms in the above lists indicates a horizon at or very near the base of the Chico formation. A similar fauna, with some additions, occurs in the sandstones at Texas Springs and near Horsetown, Shasta Co., Cal., and has been regarded as proof of the blending of the Shasta and Chico faunas,‡

* Mesozoic Fossils, Vol. I, pt. IV, p. 287, Ottawa, 1900.

† Mesozoic Fossils, Vol. I, pt. IV, p. 286.

‡ Stanton: The Faunas of the Shasta and Chico Formations. Bull. Geol. Soc. Am., Vol. IV, pp. 245–256.

partly because the beds at Horsetown had long been thought to belong to Gabb's Shasta group, and had even given the name, Horsetown beds, to the upper division of the Shasta. It is evident, however, from White's somewhat vague definition of the Horsetown beds that the term was meant to include the strata immediately above the Knoxville that contain the fauna so well developed on the north fork of Cottonwood Creek, in the neighborhood of Ono, and which really has no close relationship with this basal Chico fauna of Texas Springs, Horsetown, and elsewhere. The confusion has, doubtless, been increased by incorrect identifications of fragmentary fossils. It is not intended to deny that there are species common to the Horsetown and Chico faunas, but when the formations are properly restricted the number of common species is not as great as I once supposed, and the sandstones at Horsetown and Texas Springs containing the above-mentioned fauna belong to the Chico rather than to the Horsetown.

"This lower Chico horizon is known to occur at a number of localities in Oregon, as Jacksonville, Grave Creek, and Crooked River, usually resting unconformably on pre-Cretaceous rocks. The beds at the ''49 Mines' near Phœnix, Oregon, described by Anderson, probably represent about the same horizon. From the fossils published by Whiteaves it seems that this horizon probably occurs in the Queen Charlotte Islands on the shores and islands of Skidegate Inlet and probably of Cumshewa Inlet, where it has been grouped in the 'lower shales and sandstones' with beds that are considerably older. During the last field season I have seen evidence that it is also represented, though with a different faunal facies, in Los Angeles and Riverside Counties, Southern California. In this region, as at many of the northern localities, it is not accompanied by older Cretaceous beds, thus indicating a general and widespread transgression of the sea upon the land at the beginning of the Chico epoch."

At Mitchell, about eighteen miles northwest of Spanish Gulch, there is exposed a thick section of sandstone, conglomerate, and shale, lying below an early Tertiary formation. The upper portion of this section is made up of sandstones and conglomerates resembling the Chico at Spanish Gulch. The lower beds are shale,

FIG. 1. TYPICAL EXPOSURE OF CLARNO FORMATION, PINE CREEK, NEAR CLARNO'S FERRY.

FIG. 2. TYPICAL EXPOSURE OF MIDDLE JOHN DAY, TURTLE COVE.

with only an occasional harder stratum. The lithological characters of the lower divisions exactly duplicate those of the Knoxville as it is usually developed in California and south central Oregon. The shale seems to be capped by gravels and contains in the midst of the section a great mass of an unknown eruptive.

The total thickness of the two formations could hardly be less than three or four thousand feet, of which the shales appear to make up the larger part. The whole section is finely exposed in the bluffs along Bridge Creek at Mitchell. It dips 20° to 30° to the southeast and probably forms the west side of a syncline of which the Spanish Gulch exposure is the other limb. The whole area between Spanish Gulch and Mitchell is covered by Tertiary.

At the lower end of the Knoxville section the dip of the shales changes to westerly. Only a small portion of the western limb of this anticline is however exposed, as the Tertiary formations mantle over it.

EOCENE, CLARNO FORMATION.

At numerous localities along the western side of the John Day basin, there are exposed, either below the lowest John Day beds or above the Chico Cretaceous, several hundred feet of strata which certainly do not belong to either of these horizons. To these beds the name Clarno formation has been applied by the writer.*

Typical exposures of the Clarno are to be seen at Clarno's Ferry on the John Day east of Antelope, near the town of Fossil, on Cherry Creek, and near Burnt Ranch.

The Clarno formation is made up almost entirely of erupted materials. Part of the section consists of rhyolite and andesite flows, but the most characteristic portion comprises sedimentary beds grading from ashy shale to coarse tuff. The ash and tuff beds frequently contain plant remains in abundance and were evidently, at least in part, deposited in water. The strata seem in some places to have accumulated very rapidly. At one locality where large specimens of *Equisetum* have been found in shaly beds, the stems are standing erect and cutting across the stratification planes. This could occur only where deposition or shifting of the

*Jour. Geology, Jan.–Feb., 1901, Vol. IX, p. 71.

ashy mud was taking place very rapidly. The wide extent of the plant beds, which seem to be present at nearly all of the well-known occurrences of the formation, indicates the existence of lacustrine conditions, intermittently at least, over this region during the Clarno epoch.

The thickness of the Clarno formation is not less than 400 feet. It will probably be found to exceed that limit. The strata are usually gray to buff but sometimes show brilliant coloration in shades of red, green, and blue.

The relations of the Clarno to the Cretaceous may be seen just east of the town of Mitchell, where a considerable thickness of andesite and tuff is resting upon the Chico. Again, on the wagon road between Allen's Ranch and Mitchell, the Clarno appears to rest upon the western side of the Knoxville anticline.

Where the Clarno has been found in contact with the John Day there is no apparent angular unconformity of the strata. The difference in induration and weathering is, however, very noticeable. The sedimentary parts of the Clarno show a much greater degree of induration than the John Day beds immediately above, and tend at all localities to form steep bluffs ornamented frequently with balanced rocks or grotesque figures. The soft beds of the Lower John Day normally weather into rounded, mud-covered domes or more gently sloping banks.

On the river above Clarno's Ferry, this formation dips about 15° to 25° to the north and beneath the Lower John Day. Fine exposures continue along Pine Creek east of the Ferry. North of the town of Fossil the Clarno is again seen typically developed and dipping under the John Day. Along Currant Creek it is well exposed and is close to, or in contact with, the Columbia lava.

At most of the localities mentioned the Clarno shows a considerable thickness of lava beds toward the top. These flows are not, however, the uppermost part of the section. The base of the formation is formed by andesite flows in several places but it was not determined whether the whole section is present at these points.

At most of the Clarno localities where careful collecting has been done, plant remains are found to be fairly abundant.

Repeated attempts have been made to obtain vertebrate or invertebrate fossils also, but, so far as the writer is aware, none have ever been discovered. The plants are, perhaps, most common in a bed of tuff and ash, 100 or more feet in thickness, belonging to the middle or the lower part of the formation. The remains from Cherry Creek belong to this horizon.

In the section at Clarno's Ferry, plants are found at two horizons. The lower one, exposed two or three miles above the Ferry, appears to be the same bed as that cropping out at Cherry Creek. The leaves of the upper horizon were found about one and one-half miles east of the Ferry in a hard shale which weathers to the buff, but is, according to Mr. Calkins, reddish-brown when not exposed. The shales show considerable disturbance and are highly indurated. The Lower John Day resting directly upon them is quite soft and weathers into the mud-covered slopes so characteristic of its outcrops. It seems probable to the writer that the Lower John Day rests unconformably upon these leaf shales.

At Allen's ranch,* on Bridge Creek, leaf beds have been discovered by Condon at the base of the John Day section. The plants occur there in a reddish shale which weathers whitish. Though the writer was unable to find the original locality, he has been assured by Professors Condon and Joseph Le Conte, who visited it together, that the leaf shales belong to a formation which is covered unconformably by the John Day. Mr. F. C. Calkins and Mr. V. C. Osmont, who have collected at this locality, also inclined to the view that these beds are pre-John Day.

The writer observed typical Lower John Day close to typical Clarno near the original Bridge Creek locality. It would seem that on purely stratigraphic and lithologic grounds the Upper Clarno and the Bridge Creek leaf shales might be considered as the same horizon.

The collections of fossil plants, made by the University expeditions, were all placed in the hands of Professor Knowlton, of the U. S. National Museum, who has kindly furnished the following tentative statement regarding the Clarno flora:—

"It was at first intended to make the present contribution as

*Commonly known as the Bridge Creek locality.

complete a discussion of the fossil floras of the John Day region as possible, but after working on these collections for a short time it was found that so many changes were necessary, and so many new forms must be characterized, and more especially that other allied floras must be considered, that it would take the paper beyond reasonable limits of size. Hence, it was decided, with the consent of Dr. Merriam, to present here a preliminary and tentative list of the species obtained by him, with such geological conclusions as seem warranted at this time, and reserve the final and complete results for publication in the form of a bulletin of the U. S. Geological Survey. Much of the manuscript for this has already been prepared, but before it can be satisfactorily completed it will be necessary to thoroughly revise all of the late Tertiary floras of the Pacific Coast, more especially the Auriferous Gravels and allied formations of California. It is hoped that this may be ready for publication by the close of the year.

"The collections from Bridge Creek are of considerable size and contain much interesting material, but the collections from most of the other localities are small and fragmentary, consisting in some instances of single specimens only. Following is an enumeration of species arranged according to localities. All new species are indicated by 'n. sp.,' the names and descriptions being reserved for the final publication."

BRIDGE CREEK, Allen's Ranch.
[Locality 811.]

Sequoia langsdorfii (Brgt.) Heer.
Juglans schimperi Lesq.
Betula angustifolia Newb.
Alnus serrulata fossilis Newb.
Alnus carpinoides Lesq.
Quercus pseudo-alnus Ett.
Quercus consimilis Newb.
Quercus brewerí Lesq.
Quercus simplex Newb.
Quercus n. sp.
Quercus sp.
Ulmus n. sp.

Platanus condoni (Newb).

Ficus? condoni Newb., Proc. U. S. Nat. Mus., Vol. V, p. 512, 1883; Later Extinct Floras, p. 85, pl. LVI, Fig. 1; LVIII, Fig. 1; 1898 [1899].

Platanus aspera Newb.

Platanus sp.

Cratægus flavescens Newb.

Myrica diversifolia Lesq., Cret. & Tert. Fl., p. 241, pl. L, Fig. 10, 1883.

Grewia ermata Newb.

Fraxinus integrifolia Newb.

ROAD-CROSSING AT CHERRY CREEK.
[Locality 804.]

Asplenium subsimplex (Lesq.) Kn.

Lygodium kaulfusii Heer.

Equisetum oregonense Newb.

Juglans rugosa Lesq.

Hicoria? n. sp.

Rhamnus cleburni? Lesq.

Fragments.

ONE AND ONE-HALF MILES EAST OF CLARNO'S FERRY.
[Locality 832.]

Sequoia langsdorfii (Brgt.) Heer.

Alnus corrallina? Lesq.

Alnus carpinoides? Lesq.

Ulmus? Sp.

Acer sp.

Fragments.

THREE MILES ABOVE CLARNO'S FERRY.
[Locality 840.]

Equisetum oregonense Newb.

Zizyphus longifolia? Newb.

Aralia sp.

Aralia?

Fragments.

ONE-HALF MILE NORTHEAST OF FOSSIL.
[Locality 844.]

Sequoia langsdorfii (Brgt.) Heer.
Alnus carpinoides Lesq.
Myrica? n. sp.
Fragments.

"In attempting to work out the bearing of the plants above enumerated on the question of the age of the beds, it should not be overlooked that any conclusions drawn might be quite different from what they would be were the whole flora of each of the localities to be considered. For example Dr. Merriam's collection from Bridge Creek embraces only fourteen previously named species, whereas the complete known flora of this locality includes over forty species. And further it is impossible at the present time, without having worked out the affinities of the Tertiary floras of California and elsewhere, to give with any degree of completeness the outside relationships of the flora of the John Day region. The following conclusions, however, are not likely to be greatly modified by subsequent work.

"The oldest horizon represented by these collections seems to be that near the crossing of Cherry Creek [loc. 804]. The species though few in number seem to have their greatest affinities with forms from the lower Tertiary, and it is probable that this horizon should be referred to the lower or middle Eocene. There are a few species in common with Bridge Creek but in general its flora has a slightly older facies.

"The Bridge Creek [locality 811] as already suggested has an ample flora which is represented by a wealth of individuals. A large proportion of its species are endemic but on considering the obvious relations of these, as well as the forms known from other localities, an upper Eocene age is indicated.

"Several other of the localities seem to be of the same age as the Bridge Creek beds, namely: one and one-half miles east of Clarno's Ferry [loc. 832]; three miles above Clarno's Ferry [loc. 840]; and one-half mile northeast of Fossil [loc. 844]. Not more than three previously-named species are known from either of these localities,

and not rarely the identification of some of these is more or less doubtful, but as nearly as can be made out they should be of the same age as Bridge Creek."

It will be noticed that the determination of the plant remains, both as regards the flora as a whole and with respect to its subdivisions, agrees with the statement relating to stratigraphic succession. The Bridge Creek beds, with the few specimens from the shales one and one-half miles east of Clarno's Ferry, are considered upper Eocene, while those from Cherry Creek are held to be an earlier facies.

JOHN DAY SERIES.

Resting upon the Clarno formation and extending over the greater portion of the John Day basin, is a thick series of sediments which Marsh* called the deposits of the "John Day Lake." It has generally been referred to in geological and palæontological literature as the John Day beds. King† correlates this series with his Truckee beds as a part of the deposit of his Pah Ute Lake. In the statement regarding this correlation, King has, however, recognized Marsh's name, so that, if a correlation is attempted, Pah Ute should be displaced by John Day.

General Characters.—Nearly the whole of the John Day formation consists of ashy or tufaceous materials. Only toward the top of the section do we find typical products of erosion. At Haystack, Spray, and in the lower end of Turtle Cove, good exposures show the highest portion of the series to be composed of one or two hundred feet of hard, blocky tuff, below which is about the same thickness of sand and gravel. The gravels are in some places quite coarse, containing pebbles four or five inches in diameter. The sands sometimes show cross-bedding. Included in these deposits are worn fragments of bones and teeth, which probably represent forms similar to those in the beds immediately below.

Rhyolite flows are found toward the lower part of the Middle John Day at Bridge Creek, near the top of this division in Turtle

* O. C. Marsh, Am. Jour. Sc., 1875, 2d Ser., Vol. 9, p. 52.

† C. King. Survey 40th Parallel, Vol. 1, p. 458.

Cove, and overlying what is probably Middle John Day on Pine Creek, about three miles northwest of Spanish Gulch.

The tuffs and ashes seem in some cases to have been worked over somewhat by air or water. At other points, beds many feet thick have apparently been deposited directly, without much, if any, working over by either wind or water.

The source of the ash and tuff is as yet unknown. It probably came from vents not very distant from this basin of deposition.

Excepting the beds of sand and gravel near the top of the section, the stratification throughout the whole thickness of the John Day is very regular. Numerous beds of almost pure ash or tuff compose uniform, hard, and prominent layers, between which in the softer beds the regular deposition of thin layers is plainly indicated by delicate variations in color. Nodular layers, possibly produced in part by contained organic remains, are not infrequent in some localities, and small nodules are usually scattered through a large part of the Middle John Day.

The erosion forms and coloration of the John Day strata are quite characteristic when compared with those of other formations in the basin. In general the beds are colored various shades of red, green, blue, or yellow. In some cases they are white or gray. As will be shown later, the coloration is an important character in distinguishing the subdivisions of the system. The beds are usually quite soft and disintegrate very rapidly, forming a layer of mud several inches thick over a large part of the exposed surface. A moderately heavy rain starts the mud almost in streams, and, as it is soon formed again, erosion must proceed very rapidly. At several localities visited by the writer, groups of unrelated bone fragments, evidently brought together by collectors, were found resting on small pinnacles several inches in height, showing that in ten to twenty years erosion had progressed at least four or five inches in fairly favorable localities.

In the Lower John Day the tendency of erosion is almost always to produce dome-like, mud-covered hills, with scarcely a fragment of the bed-rock protruding anywhere. In the middle division steep, pinnacled bluffs, exhibiting beautifully the typical bad-land structure, are common, and in the uppermost division they are the rule.

Without having accurately measured the John Day section, the writer would not be willing to consider the exposures north of the southern range of mountains as representing a thickness much greater than 2,000 feet. Perhaps it is not more than 1,500 feet thick. At Sheep Rock, near Picture Gorge, the whole section is shown rather sharply tilted, and all but the lower division would be included in the column between the cap rock and the level of the river. At Bridge Creek, also, the section includes the whole of the series. It may reach a thickness somewhat over 2,000 feet at that locality.

Classification on Basis of Lithologic and Stratigraphic Characters.—Owing to the importance of determining the vertical range of the fossil forms contained in this series, it has been desirable to find some marks of recognition, besides purely palæontologic characters, by which the beds of widely-separated sections may be correlated. Though no sharply-defined dividing lines can be drawn inside the series, it is still possible, on the basis of both palæontologic and lithologic characters, to subdivide it into several fairly well-marked divisions.

Wherever the John Day is well exposed in the central and western portion of the basin, it seems to be divisible into three stages, which have been designated* the Lower, Middle, and Upper John Day.

The *lower division* consists usually of highly-colored shale, which breaks down readily, forming characteristic mud-covered domes. These beds are in the main a deep red, with occasional alternating strata of buff or white ash. At Bridge Creek alternating beds of red, white, and green, occurring in a group of the typical hills of this division, form a striking feature of the landscape, the colored strata making sharply-defined rings about the hills. At Clarno's Ferry numerous alternations of contorted and faulted, red and white beds are splendidly exposed in prominent hills at the bottom of the section.

The beds of this group appear usually to show more deformation than those higher up in the series. This may be due in part

*Science, New Series, Feb., 1900, Vol. XI, p. 219.

to their being softer and having offered less resistance to disturbances than the more rigid strata above them.

The Lower John Day is almost barren of fossil remains at all points where it was visited, and has never, so far as can be discovered, furnished many good specimens. Diligent search by the writer at several localities has been rewarded by the discovery of two or three fragments of rhinoceros teeth. An Oreodon skull was found at this horizon, many years ago, by Mr. L. S. Davis, but definite information regarding it is not now obtainable.

The lower division was estimated to be 250 to 300 feet thick at Clarno's Ferry. Its maximum thickness will probably exceed that limit. It is not impossible that the Lower John Day will sometime be found to be separated by an unconformity from the middle division. Such fossil remains as have so far been found in it indicate, however, that it belongs to the John Day series.

The *middle portion* of the John Day section at Bridge Creek, Clarno's Ferry, and Turtle Cove, consists of drab to bluish-green beds, sometimes forming rounded hills, but more frequently exposed as steep, pinnacled, and ribbed bluffs. Nodular layers and thick beds with small nodules scattered through them are common in this group, while they are rare, if not entirely absent, in the lower division, and are not common in the uppermost beds. The strata of this group are never so sharply contorted as those of the lower division, though they may stand at a fairly high angle and may show considerable faulting.

This stage has probably furnished more fossil remains than the upper division, partly because the remains are here frequently found in hard nodules, which have protected the bones and held them together.

At Bridge Creek a rhyolite flow is interbedded with the lower part of the Middle John Day, or possibly separates it from the lower division. In Turtle Cove a similar flow is found at the top of this division and possibly separates it from the upper group. At many places, particularly in Turtle Cove, hard beds of white to greenish ash and tuff are intercalated between the softer and usually more fossiliferous strata. (See Fig. 2, Pl. 7.)

The middle division is at least 500 feet thick in Turtle Cove, and possibly as much as 800 to 1,000 feet at Bridge Creek.

FIG. 1. UPPER JOHN DAY, HAYSTACK VALLEY, SHOWING SANDS AND GRAVEL. EROSION FORMS NOT PARTICULARLY CHARACTERISTIC OF THIS HORIZON.

FIG. 2. MASCALL FORMATION WITH UNCONFORMABLY OVERLYING RATTLESNAKE BEDS. NEAR MOUTH OF RATTLESNAKE CREEK.

At most John Day localities, including Bridge Creek, Turtle Cove, and the entire region of the North Fork, the *uppermost beds* in the section are buff, tufaceous, or ashy deposits, sometimes with sand and gravels near the top. These beds show a thickness of at least 300 to 400 feet, and perhaps much more in some localities. They are usually harder and are generally exposed as steeper bluffs than the strata of the lower divisions. The steepness of the bluffs is sometimes partly due to the fact that they are protected by the lavas above, but even where there is no protective covering they tend to assume the same erosion forms.

In the North Fork region, at Monument and Hamilton, red and pinkish beds, resembling the Lower John Day somewhat in color, are found next to and grading into the uppermost division. It is quite certain that some of these exposures at Monument are really Upper John Day, and a close examination shows the rock to be lithologically different from the typical basal shales. At Hamilton a considerable thickness of red beds, looking at a distance much like the typical lower division, was seen to be apparently immediately below the upper beds. It was not possible to examine the exposures and it is not known whether the middle division is missing here or whether the beds are Upper John Day similar to the red phase at Monument.

This division contains the only typical sands and gravels in the John Day and the only known remains of fresh-water mollusca occur here. Excepting a single leaf, the only plant remains known to occur in the series are in the upper division.

While it has not been possible for the writer to draw sharp lines between the divisions discussed, the lithologic characters are in general sufficiently well marked so that one is enabled to determine the horizon in the series to which beds in question belong.

Palæontologic Classification.—That the fauna of the John Day region changed considerably during the period of deposition of this series has already been shown by Wortman,* who has proposed a division of the series on a palæontological basis into lower or Diceratherium beds and upper or Merycochœrus beds. Wortman

*Extinct Camelidæ of N. America, Bull. Am. Mus., V. 10, p. 120.

mentions two species of *Merycochœrus*, *Gomphotherium cameloides*, *Elotherium humerosum*, and *Mesohippus præstans*, as characteristic of the upper division, while *Diceratherium* is the typical form of the lower division.

Dr. W. D. Matthew has recently shown that the John Day Oreodons referred to *Merycochœrus* are generically distinct from Leidy's type. Dr. Matthew has kindly furnished the following note, in which it is shown that these species should be included in a new genus, for which he has proposed the name *Paracotylops*:—

MERYCOCHŒRUS Leidy.	PARACOTYLOPS new genus.	EPOREODON Marsh.
Type, *M. proprius* (Leidy).	Type P. (*Oreodon*, *Merycochœrus*) *superbus* (Leidy).	Type *E. occidentalis* (Marsh).
Premaxillæ coossified along their entire inner margins.	*Premaxillæ* coossified at tips.	*Premaxillæ* not coossified.
Nasals much reduced.	*Nasals* unreduced.	*Nasals* unreduced.
Infraorbital foramen above m.[1–2]	*Infraorbital foramen* above p.[4] m.[1]	*Infraorbital foramen* above p.[3]
Face suddenly narrowed in front of orbits.	*Face* more gradually narrowed in front of orbits.	*Face* gradually narrowed in front of orbits.
Zygomata greatly expanded.	*Zygomata* greatly or moderately expanded.	*Zygomata* moderately expanded.
Mastoid process greatly expanded into a broad transverse plate.	*Mastoid process* of moderate size.	*Mastoid process* not expanded.
Occiput broad and short, sagittal and transverse crests nearly buried in cellular tissue.	Occiput high and narrow, sagittal and transverse crests very prominent.	Occiput high and narrow, sagittal and transverse, crests prominent.
Cellular bony tissue extensively developed on posterior part of skull.	*Little or no cellular bony tissue* on posterior part of skull.	*No cellular bony tissue* on posterior part of skull.
Neck very short.	"Neck rather short" (Scott).	Neck of moderate length.

Owing to the change in the name of the characteristic fossil of the Upper John Day, the writer suggests that this division would more appropriately be denominated the Paracotylops beds.

In correspondence regarding the relation of his classification on

the basis of faunas to that of the writer, Dr. Wortman states that his Paracotylops (Merycochœrus) beds are doubtless the same as the upper division here proposed, and that his Diceratherium beds would correspond to the middle division. This leaves the lower division without a palæontologic designation, until its fauna shall be discovered. Attention is called in this connection to the fact that in most classifications of the continental Tertiary beds of North America this division is omitted.

The collections made by the University of California parties have all been labeled as accurately as possible in the field with reference to horizons, and it is hoped that when the material is finally gotten into form for study it will be possible to obtain more information regarding the vertical distribution of species. Judging from field observations alone, Dr. Wortman would be justified in his classification. The large *Paracotylops* forms were found to be principally, if not entirely, confined to the upper beds, the Oreodons being principally represented by *Eporeodon* in the middle division. Remains of the large Elotheres are most abundant in the buff beds, though they are known also from much lower horizons. Remains of *Gomphotherium*, probably *cameloides*, were found only in the upper division, where they are quite abundant near the junction of the North and South Forks. *Diceratherium* is certainly more abundant in the middle division, though it probably occurs in the highest beds as well.

In a special report on the purely palæontological results of the work of the expedition, this question will receive further consideration.

Extent and Stratigraphic Relations.—The John Day beds are found exposed interruptedly along the John Day River and its tributaries from Clarno's Ferry up to the Picture Gorge, just below Dayville on the South Fork, and probably as far east as Granite Creek on the Middle and North Fork. North of the mountains unmistakable John Day is seen at Fossil and Lone Rock. Exposures near the town of Antelope are possibly also a part of this series. South of the mountains typical deposits are known at Logan Butte near Price.

At Bridge Creek and in Turtle Cove the whole section is

exposed. At Clarno's Ferry the lower and middle beds are well shown, and possibly the upper beds in part. About five miles below the ferry lava beds rest directly upon the middle division. Along the main river from Haystack Valley to the junction of the North and South Forks, and from there along the North Fork to Monument, it is principally the upper beds, occasionally with the middle division, that are found. On the Middle Fork the upper beds seem to be the only part of the section present between the pre-Tertiary basement and the lava.

At Fossil several hundred feet of the upper division appear between the Clarno and the Columbia lava. At Lone Rock only the Upper John Day is exposed, though the other divisions may also be present. Mr. V. C. Osmont states that south of the mountains at Logan Butte there is a great thickness of John Day beds, estimated at between 3,000 and 4,000 feet, composed of the upper and middle divisions, with possibly a portion of the lower one. The bottom of the section is not exposed. Though the exposures are not continuous, Mr. Osmont thinks that the beds are pretty certainly not repeated by faulting. Aside from the exposures at Logan Butte, the writer is not aware of the existence of any outcrops of typical John Day south of the Blue Mountains.

The widening of the basin of deposition indicated by greater extent of the upper beds may have been only toward the north, but if the southern section is, as it appears, much thicker than the northern, it is only reasonable to suppose that the basin extended for a considerable distance to the south beyond the farthest point to which it has been traced.

The John Day beds are usually slightly disturbed. They are generally tilted five to ten degrees. From the observations made by the writer, no definite system of folds could be made out, though there seem to be several which trend east and west. Faulting is not uncommon and in some places there has been much friction along the fault planes, so that the soft beds have been changed into hard slate bands several inches in thickness. Both the normal and reverse types of faults are represented. Toward the west end of Haystack Valley a break of unknown extent brings what are probably Middle John Day strata up to the level of

the highest beds of the series. At another locality, some miles east of this point, numerous thrusts are beautifully shown in cliff sections. Along the North Fork two systems of fractures were noticed. One trends north and south and the other appears to cross it at nearly a right angle.

As has already been indicated, the series is evidently unconformable upon the Clarno.

In the whole of the region occupied by John Day north of the southern range of the Blue Mountains, it is covered by the Columbian lavas, being accessible only in the deep cañons, where it has been exposed by extensive stream corrasion. At every locality in the basin where the series can be seen, its relations to the overlying formations are beautifully shown. In several places, notably at Sheep Rock in the upper end of Turtle Cove, and on the main river below Spray, residual hills in the middle of the valley are capped by portions of the lower flows, which have served to protect the softer beds beneath.

The Columbia lavas are in some places seen to be decidedly non-conformable to the John Day. Near Haystack the fossil beds form a fairly sharp anticline below lavas which are almost horizontal. At Clarno's Ferry lava flows are seen at one locality to rest upon the middle beds, the typical upper division being absent.

At many points where the contacts of Columbia lava and John Day were examined, fossil wood was found to be abundant. In one place at the lower end of Turtle Cove, where there was much petrified wood at the contact, branches of trees were found pushed up into the lava beds. Some of these stems showed an interesting mode of preservation, being unaltered charcoal on the outside, while the interior was petrified.

Evidently the John Day had been slightly crumpled, had suffered erosion for a considerable period, and was at least partially covered by forest when the first lava floods were poured out.

Mode of Deposition.—The John Day beds have generally been considered as entirely of lacustrine origin, and probably a part of the series has been formed in that way. There are, however, certain peculiarities about a considerable portion of the section which it is difficult to explain by this theory.

As has previously been stated, the John Day is largely made up of volcanic ash and tuff, which does not appear to have suffered much from working over. Sands, gravels, and muds, such as belong to characteristic lake beds, are confined to the top of the series. While molluscan remains are quite common at many horizons, fresh-water forms are known only in the sands and gravels mentioned above. The numerous molluscan shells, found in the ash and tuff beds, are of land forms. Plant remains, also, which characterize lake beds are, excepting some petrified wood, confined to the highest strata. A solitary leaf, found many years ago in the middle stage at Turtle Cove, is the only known exception to this rule. Fish remains have not been found at all in this series. Tortoise bones are very abundant, but so far the writer has not learned of the existence of any water forms of this order. The only aquatic mammalia which have been found are rodents. Remains belonging to members of the beaver family seem to occur at several horizons through the section. In short, while organic remains are abundant in the greater portion of the John Day, aquatic forms are found only in limited sections of the series. One could account for the absence of water forms by supposing the lake to have been salt or alkaline, though there does not appear to be any definite evidence in support of this view.

An objection to the lacustrine hypothesis as applied to the ashy beds is found in the fact that, while the greater part of the deposit is composed of fine material, large, isolated mammalian bones are scattered all through it and over wide areas of the same horizon. Many of these bones are evidently parts of skeletons which were torn apart and scattered about on a land surface before they were finally buried. If they were carried out into a lake it is hard to understand how they could be selected for distribution in deposits from which all other large fragments of detrital material are absent. Occasionally carcasses might be floated out into a lake and finally buried in fine deep-water deposits. In such cases many, if not all, of the bones would be found together. The presence of a considerable portion of the fossil material could not be accounted for in this way.

A possible explanation of these occurrences is that a shallow

lake on a wide plain might by expansion and contraction, or shifting its position, ultimately cover and bury bones which had been resting for a long time on the land. The same thing could be accomplished by flowing water in a basin where cutting had largely ceased, or by accumulation of wind-carried dust or ash.

The strongest argument in favor of the lacustrine hypothesis is found in the character of the bedding of the series. The stratification is nearly everywhere absolutely regular and the beds are frequently very thin. Bedding of this kind could be developed only on a floor free from all irregularities. Such deposits, where they are not shown to have accumulated rapidly, are usually considered as having been formed in water.

Recently W. D. Matthew has suggested* that the White River beds, which the John Day resembles in a measure, are in part of æolian origin. Except for the regularity and thinness of the bedding, such an hypothesis as this applied to the question of the origin of the John Day would have much in its favor. The material being largely ash, there would be no difficulty in accounting for its origin. If the deposits were formed rapidly enough to prevent dissection, absolute regularity of bedding could be maintained. Here again, however, we meet with a difficulty, as it is hardly probable that a region subjected to frequent ash showers would be inhabited by such numbers of large mammals as would seem to have lived there. If the deposition took place at intervals infrequent enough so that the region could be a desirable place of habitation, it is probable that under ordinary conditions irregularities of the surface would cause noticeable unevenness in the bedding. That the accumulation of the John Day beds occupied a long period is brought out by a study of the vertical distribution of the species, which changed considerably during this epoch.

The thinness of the bedding in places might be urged as an argument against a purely æolian mode of deposition. The writer is not familiar with any æolian deposits that have accumulated slowly, which show thin and well-marked bedding planes.

A theory of fluviatile origin of the series would be open to

*Am. Naturalist, May, 1899, Vol. 33, p. 403.

some of the same objections that have been made to the æolian theory.

A large part of the John Day seems to have been deposited under conditions somewhat different from any that have been generally recognized as governing the accumulation of extensive formations. Other somewhat similar deposits on this side of the continent appear to have been formed in much the same way.

Having originally held to the lacustrine theory of origin for the whole series, it would seem to the writer, after consideration in lights most favorable to this theory of all the evidence obtainable, that, as commonly accepted, it fails to meet fully the necessities of the case for a large part of the section. If it is retained for these beds it will be in some modified form.

The writer would suggest that showers of ash, with tuff deposits, on a plain, occupied perhaps in part by shallow lakes, like the so-called lake-beds of the prairie region of the central plains, might form accumulations similar to those in a large part of the series. If the basin were kept close to base level, irregularities of the surface would hardly be noticeable. Rapid deposition of ash or tuff would occasionally form homogeneous beds of considerable thickness, and would, perhaps, make the region temporarily uninhabitable for most forms of animal or plant life. During the intervals between such periods of rapid deposition, the surface might be partially covered with vegetation and become the home of such animal forms as have left their remains in the fossil beds. The deposition of small quantities of ash during these periods would not necessarily be a hindrance to the occupation of the region by animals or plants, more than the deposition of loess-like dust in the central plains region has prevented its habitation by a complex fauna and flora. Future investigations may show that some of the very thin-bedded portions of the ash deposits were laid down in water, and that the less distinctly stratified beds are largely Æolian.

Fossil Remains.—The mammalian and molluscan faunas of the John Day are already fairly well known from the numerous contributions to the palæontology of this region by Marsh, Cope, Scott, Wortman, Stearns, and others, and the objects of this paper do not require a further consideration of this subject.

The flora of the John Day was unknown until the summer of 1900, when a small collection of leaves was obtained by the University of California party from the upper beds near Lone Rock. These specimens were examined by Professor Knowlton, who reports upon them as follows:—

"Three and one-half miles south of Lone Rock [locality 861].

Sequoia langsdorfii (Brgt.) Heer.

Juglans n. sp.

Salix sp.

Phyllites n. sp.

Fragments.

"The locality south of Lone Rock [loc. 861] is represented by a single known species. It is impossible to settle the age from these data, but judging from the affinities of certain of the new forms detected this horizon is possibly not far from that of the Van Horn's ranch* material. Much larger collections must be made before the age can be satisfactorily determined by the plants."

COLUMBIA LAVA.

The name given to the lava formation above the John Day was first used by I. C. Russell†, who applied it to the series of eruptives which forms such a prominent feature of the geology in the area drained by the Columbia River. In the region discussed by Russell there are several distinct horizons of Columbia lava, separated by important formations belonging to different geological periods. Obviously only one of them can retain the name, if it is to be used as a series or formation name in geological classification. This one should be the horizon which is most prominent along the Columbia River, as it was this formation which suggested the name. In the John Day basin it is found that the lavas of the Columbia form a well-defined series which lies between the John Day and the Mascall formations. Other eruptives in this region are hardly to be confused with it. This series is, moreover, that one of the several to which the name is applied which has the greatest lateral

*Mascall formation.

†Bull. No. 108 U. S. Geol. Survey, p. 20.

extent, forming probably the largest lava field of the world and one of the most important formations on this continent. It would seem advisable to restrict the name Columbia lava to this horizon.

The lava series is composed of a large number of basalt flows which are sometimes separated by beds of tuff. At Turtle Cove twenty-three flows were counted in the bluff. Nowhere does it seem to be less than 1,000 feet thick, and it would average much above that over the greater part of the basin.

Though no attempt was made to trace out any of the flows, it was noted that some of them seem to extend for many miles.

A hint as to the mode of exit of the lava is furnished by the occurrence of basaltic dikes in the John Day beds at many localities. The largest and most important of those that have come to the writer's notice are the Davis dikes, which run in nearly a straight line, with few if any breaks, for about fifteen miles through the lower end of Turtle Cove and out into the valley of the main river. The dike shows transverse columnar structure at most points. At the only place where its thickness was estimated, it was about twelve feet in diameter, but it certainly reaches several times that width along a good part of its course.

In most places where the contact of dikes with the fossil beds was observed, the bounding walls seem to have suffered little, if any, change. At one point, however, on the west side of Turtle Cove, where the Davis dikes cut the Upper John Day, a most interesting contact phenomenon is noticeable. The ashy fossil beds here exhibit a most remarkable development of columnar structure for a distance of about fifteen feet from the lava on each side. The columns are approximately normal to the surface of the dike and fairly straight. The faces are very even, the columns being as regular and sharply cut as the most perfect structures developed in basalt. The dike at this point is multiple, and portions of the fossil beds caught between the leaves have also developed columnar structure, with this exception, that the columns are there much larger than those bounding the dike on the outside. The outer columns are noticeably small, averaging about two inches in diameter, even when ten or more feet in length; while some of those developed in a band of John Day

deposit about two feet thick, caught in the midst of the dike, show a diameter of about five inches. Evidently the greater heat and slower cooling tended to increase the size of the columns.

As far east as the writer's observations extend, viz., to Dale on the north and Mt. Vernon on the south, the Columbia lava has formerly covered the whole country. There do not appear to have been any islands in this sea of stone. Over most of this region the lava beds still remain fairly flat. They are rarely inclined more than five or ten degrees.

Along the north side of the East Fork Valley from Mt. Vernon to Picture Gorge, and from there westerly toward Caleb, the Columbia lavas are inclined sharply to the south. Along the valley they pass beneath the river and below the Mascall formation. At Picture Gorge, where the lavas are cut through by the river, they show a dip of about twenty degrees or more to the south. On the south side of this valley the southern range of the Blue Mountains is capped with Columbia lava. In the Crooked River region the lavas appear again beneath the Mascall formation.

Viewing the East Fork Valley from near Caleb it is quite evident that the Columbia lavas are sharply faulted or bent along its south side, the downthrow being to the north. Near the western end of the valley a number of nearly vertical beds are exposed high up on the southern slope. Persons who have visited these outcrops inform me that they are lava, and I have supposed them to be beds dragged down along the plane of a fault or sharp fold. In the depression to the north of the fault plane there rest several post-Columbia lava formations which, as will be shown later, have also been affected by this disturbance.

MASCALL FORMATION.

Nomenclature.—Along the valley of the East Fork and south of the Blue Mountains, there is found, resting upon the Columbia lava, a series of sediments which have been known in the literature as the Cottonwood* beds, the Loup Fork† beds, the Ticholeptus‡

*Bull. Am. Mus. Nat. Hist., Vol. XII, p. 23, also Jour. Geol., V. IX, p. 72.
†Manual of Geology, 4th Ed., J. D. Dana., p. 895.
‡E. D. Cope, Am. Nat., 1886, V. 20, p. 367.

beds (in part), and the Amyzon* beds. Recently Wortman has placed his palæontological horizon, known as the Protolabis† beds in this formation. None of these names appear to be applicable to the formation considered as a stratigraphic unit. The term Cottonwood is pre-occupied, having been used for a carboniferous formation by Prof. C. S. Prosser. It is very doubtful whether it can ever be shown that this series and the true Loup Fork occupy the same horizon in the standard geological scale. As yet it has not been done. The Ticholeptus beds probably belong to another horizon than the one with which we are dealing. The correlation of this series with the Amyzon beds was due to its confusion with the Clarno at Bridge Creek. Wortman's Protolabis beds will doubtless be found to cover a considerable portion of this formation, but as the section is perhaps a thousand feet or more in thickness it is almost probable that it will be found to represent more than one palæontological horizon. It is, moreover, advisable to separate palæontological horizon names from those used for formations or stratigraphic units. It is, therefore, proposed to designate these beds as the Mascall formation. The typical exposure is near the Mascall Ranch, four miles below Dayville.

Occurrence and Stratigraphic Relations.—In the valley of the East Fork the Mascall formation rests in the depression formed by the deflexed Columbia lavas. (See Fig. 1.) The dip of the lower beds is here approximately the same as that of the lava beds below them; the uppermost strata may be slightly flatter. On Birch Creek and at several other localities, there is some evidence of intercalation of lava flows between the lower strata. The Mascall beds do not reach to the level of the lava plateau to the north, though they may formerly have passed over it. They have suffered much erosion and a later formation rests upon their worn edges. So far, the writer has learned of no deposits corresponding to the Mascall in the northern part of the basin. The Ellensburg beds of central Washington, described by Russel,‡ are probably

*E. D. Cope, Proc. Am. Phil. Soc., 1880, V. 19., p. 61.

†J. L. Wortman, Bull. Am. Mus. Nat. Hist., V. X, pp. 120, 141.

‡Bull. 108, U. S. Geol. Surv., p. 22., also 20th Ann. Rep., U. S. Geol. Surv., Part II, p. 127.

Fig. 1. Sketch of John Day Valley between Picture Gorge and Dayville. Gorge cut in Columbia lava. Mascall formation resting on lava and covered by Rattlesnake beds.

in part of the same age, but may have accumulated in a different basin.

At Rattlesnake Creek near Cottonwood the Mascall is not less than 800 to 1,000 feet thick. The beds are made up largely of ash and tuff and are generally light colored, though there are some brownish and reddish strata. Coarse detrital materials are generally absent from the typical section on the north side of the East Fork Valley.

Six miles above Dayville there are exposed along the south side of the valley about 400–500 feet of conglomerate, sand, ash, and tuff, forming a syncline pitching to the southeast. The steepest dip seen in the main section here is about 30°, but at the foot of the bluff there are some exposures of gravel beds which are nearly vertical. Pebbles from several horizons in this section were examined, but none seemed to be derived from the Columbia lava. Two other exposures of gravel were seen some miles west of this point, also on the south side of the river. Whether these beds are upper Mascall or whether they belong in some other formation is not clear to the writer. Fragmentary leaf remains were found about the middle of the section, and sufficient material could possibly be obtained there to throw some light upon the age of the horizon.

Fossil Remains.—The Mascall formation has furnished many fossil remains, including those of mammals, testudinates, fish, and

plants. The vertebrate fossils are neither so numerous nor so well preserved as those in the John Day. Teeth and single bones comprise the greater part of most collections made here. The mammalian remains show the fauna to have been of a much more specialized and higher type than that of the John Day.

Fish remains are found associated with plants in the lower part of the formation near the old Van Horn ranch. The single species known from this locality has been referred by Cope* to the genus *Plioplarchus*, a member of the perch family.

Plant remains are very abundant in the shales at Van Horn ranch and other localities near the bottom of the section. The collection made here by Captain Bendire was studied by Professor Lesquereux, who considered it upper Miocene. A collection made by the University party in 1900 was submitted to Prof. F. H. Knowlton, who has furnished the following list, with a statement regarding the probable horizon to which the flora belongs:—

"Van Horn's Ranch, about half way between Cañon City and Dayville on East Fork. [Locality 878.]

Glyptostrobus ungeri Heer.
Taxodium distichum miocenum Heer.
Idnyites sp.
Salix angusta Al. Br.
Quercus pseudo-lyrata Lesq.
Quercus pseudo-lyrata acutiloba Lesq., Proc. U. S. Nat. Mus., vol. xi, p. 17, pl. xi, fig. 1, 1888.
Quercus pseudo-lyrata brevifolia Lesq., op. cit., p. 18, pl. x, fig. 2, 1888.
Quercus pseudo-lyrata latifolia Lesq., op. cit., p. 18, pl. xii, fig. 1, 1888.
Quercus pseudo-lyrata obtusiloba Lesq., op. cit., p. 18, pl. x, fig. 3, 1888.
Quercus n. sp.
Quercus n. sp.
Quercus? sp.
Planua ungeri Ett.

*Am. Nat., 1889, V. 23, p. 625.

Ficus? oregoniana Lesq.
Laurus n. sp.
Aralia whitneyi? Lesq.
Acer bendirei Lesq.
Acer dimorphum Lesq.
Acer n. sp.
Sapindus obtusifolius Lesq.
Prunus n. sp.
Prunus n. sp.
Hydrangea bendirei (Ward).
Marsilea Bendirei Ward, Sketch of Paleobotany, 5th Am. Rept. U. S. Geol. Surv., p. 446, 1883–84.
Povana Bendirei (Ward) Lesq., Proc. U. S. Nat. Mus., vol. xi, p. 16, pl. viii, fig. 4, 1888.

"Gravel and tuff section, south side of East Fork Valley. Four miles east of Dayville. [Locality 880.]

Carpinus grandis Unger.

"The flora of Van Horn ranch [loc. 878] finds its greatest affinity with the Auriferous gravels and allied floras of California and is to be regarded as upper Miocene in age.

"The locality four miles east of Dayville [loc. 880] is represented by a single species. A larger collection from this locality will be needed before the age can be satisfactorily determined by the plants."

It is the plant and fish horizon of the lower Mascall which Cope referred to the Amyzon beds. It was apparently supposed to have the same relation to the John Day as the Clarno leaf beds at Bridge Creek.

Origin.—The numerous remains of plants and fish in the fine white beds at Van Horn Ranch indicate lacustrine conditions at this locality during the early portion of the period. Similar leaf beds in the Crooked River region which have been described to the writer possibly originated in the same way and at or near the same time.

In the upper part of the section at Cottonwood, the conditions of deposition, so far as can be ascertained, seem to have been similar to those under which the John Day was laid down. Should

the gravels on the south side of the East Fork valley prove to be the uppermost beds of the Mascall formation, the era of deposition would appear to be concluded in a manner similar to that in which the John Day ended.

RATTLESNAKE FORMATION.

Throughout the length of the Mascall formation exposures in the valley of the East Fork, they are seen everywhere to have been capped at one time by a series of later deposits which have sometimes been confused with them. To these beds the name Rattlesnake formation is applied by the writer, the typical occurrence being on Rattlesnake Creek about one mile west of Cottonwood. The Rattlesnake has been referred to by Wortman and Matthew* as the "gravels" at the top of the Cottonwood section. Possibly Cope also refers to them in an indirect way, though the writer is not able to determine certainly just what is meant by his statement.

Stratigraphy.—In Fig. 2, Pl. 8, and Fig. 1, p. 307, the typical exposures of the Rattlesnake show it resting unconformably upon the Mascall. It is usually inclined only slightly, having a southerly dip of about five degrees. At one locality on Birch Creek where a section of the Rattlesnake was carefully examined, it was found to comprise 30–40 feet of coarse basal gravels, above this about 25 feet of soft brown tuff, and capping this about 30 feet of rhyolite At other localities more than 100 feet of gravel have been seen upon the rhyolite. The basal gravel beds show a thickness of 200 feet or more in other localities. They are frequently very coarse and contain many pebbles evidently derived from the Columbia lava.

In the Birch Creek section the base of the rhyolite flow is filled with angular pebbles of Columbia lava. A stratum about one foot thick at the bottom is largely made up of pebbles, and above that, at least half way up to the top of the flow, pebbles are found scattered through the mass. The rhyolite exhibits everywhere a tendency to split up into large irregular columns about twenty-five feet across. At several localities near the mouth of Beach Creek, a radial or boquet-like columnar structure is beautifully developed

*W. D. Matthew, Bull. Am. Mus., V. 12, p. 23.

in it. The columns are here about 12–15 inches in diameter. They are sharply separated from each other and show remarkable regularity. The rhyolite extends as a very uniform flow for at least fifty miles westward from Mt. Vernon. It is said by Mr. Osmont to reach up the valley at least 15 miles above Cañon City. Osmont also states that it caps the Mascall formation in the Crooked River region. Being much more resistant than the underlying beds, it has tended to form broad tables or terraces wherever it occurs.

Fossils.—The Rattlesnake gravels contain many vertebrate remains, most of which have heretofore been listed with the Mascall fauna. The Rattlesnake fossils when weathered out are frequently to be found resting upon the Mascall beds below, and as most of the material from both Rattlesnake and Mascall is found detached from the matrix, the difficulties in the way of separating the faunas are considerable. So far no segregated lists of the species have been published.

Basin of Deposition.—The floor upon which the Rattlesnake was laid down consisted largely of the upturned and eroded Mascall beds. The basin of deposition was bounded on the north by a range of hills formed by the upper portion of the Columbia lava monocline. At the present time the northern limits of the basin may be clearly seen, as large portions of the deposit have escaped erosion and extend along the northern side of the East Fork valley and westward to the divide some miles beyond Caleb. These considerable remnants all fall into a nearly horizontal plane which abuts against the lava hills to the north. Looking out over the Rattlesnake table-lands from Spanish Gulch one can see an almost continuous series of these deposits, which are in nearly their original position and have not suffered greatly from erosion. It requires no great effort for one to picture to one's self this part of the basin in its original form.

Deformation.—At Picture Gorge, on the north side of the valley, the Rattlesnake rhyolite extends to within a few yards of the Columbia lava and would rest upon it if the section were not interrupted by the gorge. On the south side of the valley it is not well represented, and, where present, is frequently much broken up.

The southerly inclination of this bed and its broken character on the south side of the valley indicate that considerable movement has taken place in post-Rattlesnake time along the plane of the fault which has broken the Columbia lava at this point. This movement is a continuation of that which had given the Mascall formation a southerly dip before the Rattlesnake was deposited upon it.

South of the Blue Mountains, according to Osmont, the rhyolite flow appears again in its typical form and rests upon the Mascall formation.

The present drainage of the John Day must have been established before the tilting of the Rattlesnake took place, as the river now turns sharply to the north at Picture Gorge, leaving the soft deposits of Mascall and Rattlesnake, which extend farther to the west in the direction which the stream has run for many miles, and cutting straight through the Columbia lava monocline. Had the movement taken place before the cutting of this gap was initiated, the river would probably have been thrown toward the southern side of the valley and would never have come out at this point.

Age of the Rattlesnake.—Without making any attempt at exact correlation of the Rattlesnake with any other formation, there seems to be sufficient evidence to show that it should be considered as belonging to the Pliocene of the standard scale; perhaps it represents only the later portion of that period. Its stratigraphic relations to the Mascall formation are such that it could not be older than early or middle Pliocene, while the amount of erosion which took place between the close of this epoch and the middle or latter part of the Quaternary shows that it could not possibly be later than Pliocene.

QUATERNARY.

Terraces.—At numerous points along the John Day and its tributaries, one or more terraces are to be found not far above the existing floor of the valley. At the upper end of Haystack Valley on the main John Day, gravels containing numerous large rounded pebbles of rocks not outcropping in that neighborhood are exposed

on a terrace about 75–100 feet above the river. Twenty-five feet below this is the sagebrush flat made up of alluvium with numerous angular boulders and pebbles from the hills near by. At another locality, about two miles farther up the river, water-worn gravels were again seen on well-marked benches.

Along a considerable part of the river, terraces representing parts of ancient alluvial fans or slopes are very common. On the north side of Bridge Creek near Allen's ranch numerous broad, gently-sloping tables separated by gullies sometimes several hundred feet deep represent an old and very regular alluvial slope. The stream cuttings here show in places a considerable thickness of the John Day beds capped by irregularly stratified wash from the adjacent lava bluffs.

In terrace deposits remains of *Elephas* and *Equus* have been found at several localities. Near Mt. Vernon, on the East Fork, a nearly complete skeleton of *Elephas primigenius* was discovered in an alluvial deposit not much above the level of the river. Whether or not the other remains have been worked over from older deposits, this skeleton has evidently not been disturbed.

Cañon Cutting.—The discovery of typical Quaternary forms in deposits so near the valley floor shows that the cañon cutting had been practically finished for some time when Quaternary mammals were still in this region. In other words, the period of active cañon-cutting did not extend to the close of the Quaternary. The backward extension of this period is limited by the Rattlesnake. Though the drainage was probably established before the close of that epoch, the great work of corrasion was accomplished after the river began cutting into the uppermost Rattlesnake beds. A palæontological determination of the age of the Rattlesnake would very materially aid in fixing more exactly the probable earlier limit of the era of cañon-cutting. The greatest probable extension of this epoch is from late Pliocene to middle Quaternary. On these broad lines a correlation of this period with the Sierran * epoch of Le Conte would seem to be justified.

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*Jour. Geol., 1899, V. 7, p. 525.

Ash Beds.—At many localities, particularly in the northern part of the John Day basin, an ash bed of comparatively recent origin is seen in the flood plain deposits or on the alluvial slopes near the streams. In the upper end of Haystack Valley a stratum about 1½ feet thick is exposed at several places in the river bank. It is here covered by 6–10 feet of alluvium with angular pebbles. On Rudio Creek there are fine exposures of an ash bed along the bank of the stream. The bed is here much thicker than at Haystack. Similar deposits were seen as far east as the writer has explored.

Though deposits somewhat similar to those described might be formed by material washed down from fossil beds or other deposits of volcanic materials, the origin of these beds can not be ascribed to such a cause. Where they have been carefully examined the ash is perfectly pure and is sharply separated from the deposits above and below. It has apparently not been worked over appreciably and was probably deposited rapidly, otherwise it would be mingled with other detrital material. Its deposition is evidently to be correlated with some catastrophic volcanic outburst occurring in comparatively recent times. Possibly it has been derived from the volcanoes of the Cascade Range.

University of California,
April, 1901.

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MINERALOGICAL NOTES.

BY

ARTHUR S. EAKLE.

WITH CHEMICAL ANALYSES, BY W. T. SCHALLER.

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I. PECTOLITE, DATOLITE, AND OTHER MINERALS OCCURRING NEAR FORT POINT, SAN FRANCISCO.

THE coast rock on the southern shore of the Golden Gate, extending for some distance on both sides of Fort Point, consists of serpentine, which represents the northern outcrop of the great serpentine laccolith, extending across the city of San Francisco, intrusive in the Franciscan sandstones. This mass of serpentine has been described by Palache,* and classified by him as a lherzolite-serpentine. Numerous boulders of serpentine are strewn along the beach west of the fort, which show manifold varietal differences in color and structure, and contain abundant veins of secondary

*"The Lherzolite-serpentine and Associated Rocks of the Potrero, San Francisco," this Bulletin, 1894, Vol. 1, pp. 161–192.

minerals, thus offering a very interesting field for mineralogical study. The main mass of serpentine is dark green, with often a mottled appearance, due to numerous phenocrysts of original enstatite, which show shining bronze-colored cleavage faces. Narrow veins of very compact light green serpentine traverse the dark green boulders, and these are generally accompanied by thread-like veins of finely-fibrous chrysotile, which form a border on each side of the light green.

Among the secondary minerals, forming the white veins, which so abundantly seam the serpentine, magnesite appears the most common. It is snow white and very compact and hard usually, but where the mass of serpentine is much decomposed, the mineral occurs in small botryoidal forms, and is softer, owing, probably, to an alteration in part to hydromagnesite. Calcite is also abundant, mostly in cleavage masses, sometimes in small scalenohedra. Long and slender colorless prisms of aragonite, white tabular crystals of barite and small gypsum needles are also occasionally found in the fissures. Grayish-brown opal occurs in small rounded inclusions in the serpentine on the east side of the fort.

A few hundred yards west of the fort a large mass of rock outcrops on the shore of a different nature from the serpentine, and is probably a remnant of an older basic rock included in the serpentine. The mass has a foliated or somewhat schistose structure due to shearing, and is highly altered to chlorite, and contains the veins of pectolite and datolite.

Pectolite.—The numerous pectolite veins are generally very narrow, sometimes mere white threads, but occasionally they widen out to several inches, the one from which most of the specimens were collected being about four inches in width. The mineral is fibrous and generally very compact and tough, with a more or less radiated structure. In some parts of the vein the fibers are coarser and not so densely compacted. On one specimen short and rather broad prismatic crystals, considerably rounded by wave action, occur. They apparently consist of a broad base $c(001)$, a broad orthopinacoid $a(100)$, and two prisms, perhaps (540) and (140), as indicated by measurements with the contact goniometer. The color of the mineral is snow white, but much of it is stained reddish by varying amounts of ferric oxide.

A mean of two analyses of the whitest mineral is:—

SiO_2	53.40
Al_2O_3, Fe_2O_3	3.87
CaO	30.56
Na_2O	7.61
H_2O, ignition	4.46
	99.90

Datolite.—Veins of datolite are about as numerous as those of pectolite in the rock and the two minerals frequently occur together in the same fissure. Many small druses of clear, colorless datolite crystals occur, and these furnished the best crystals for measurements. One vein about six inches wide is composed of calcite, pure white kaolin and datolite, intimately mixed, and some of the datolite crystals in this vein reach a dimension of a half centimeter in length and width.

The orientation for datolite, chosen by Dana in his "System of Mineralogy,"* instead of the one commonly adopted by the German mineralogists, is the most natural one for these crystals, and is, therefore, adopted here in the accompanying figures, using his axial ratio also.

Owing to the characteristic wavy and striated faces on the crystals, the measured angles with the reflecting goniometer varied considerably, but they served for the complete identification of the forms, a total of nineteen being observed, as follows:—

$c(001)$	$x(102)$	$\lambda(\bar{1}13)$
$a(100)$	$u(104)$	$\mu(\bar{1}14)$
$m(110)$	$\xi(\bar{1}02)$	$\omega(\bar{1}16)$
$o(120)$	$n(111)$	$q(312)$
$M(011)$	$\nu(\bar{1}11)$	$\beta(121)$
$g(012)$	$\varepsilon(\bar{1}12)$	$\pi(\bar{2}31)$
		(1.1.18)?

*E. S. Dana, "System of Mineralogy," 1890, p. 502.

$m(110)$ is the predominating form and is represented usually by broad wavy faces.

$c(001)$ is common, with generally small faces which are characteristically striated parallel to the positive pyramidal edges.

$a(100)$ is not very common, and the faces are generally narrow.

$n(111)$ and $e(\bar{1}12)$ are the common pyramidal forms and are always well developed.

$M(011)$ is always present and the faces are long and narrow.

$g(012)$ occurs on but few of the crystals, and then as very narrow faces. This is the unit prism of the German mineralogists.

$x(102)$ rarely occurs, and the faces are always dull or etched.

(1. 1.18)? This form was observed on two crystals, as narrow faces.

	Angles measured.	Calculated for symbol.
(001):(1.1.18) =	7° 15′	7° 35′
	7° 25′	

The base on both crystals was striated and the readings were consequently not perfect enough to place the symbol for the form out of doubt, since the form makes such a small angle with the base.

The remainder of the forms observed are represented by quite narrow faces, and are of rarer occurrence on the crystals, a large majority of the crystals having the combination $m(110)$, $c(001)$, $n(111)$, $e(\bar{1}12)$, and $M(011)$. Figure 1, Pl. 9, shows this combination and also the general habit of the crystals.

A rarer type is tabular parallel to the base and has a comparatively broad face of $a(100)$ in addition to the other forms. This is seen in Figure 2, Pl. 9.

Figure 3, Pl. 9, represents a type that is more elongated in the vertical direction, and with some of the narrower forms present.

Figure 4, Pl. 9, shows a more complete combination of forms with the common habit.

An analysis of the mineral showed the composition:—

	Per cent.
SiO_2	36.71
Al_2O_3	0.17
CaO	33.83
B_2O_3	22.11
H_2O ignition	6.52
	99.34

The mineral was dissolved in hydrochloric acid, and then evaporated several times to dryness, on the water bath, with the addition of methylalcohol to expel the boron, and the silica and bases were then determined. The boric acid was determined by distillation with nitric acid, and methylalcohol and the distillate then titrated. All the water was expelled at a low red heat.

II. ZIRCON CRYSTALS FROM SISKIYOU COUNTY, CALIFORNIA.

Several small zircon crystals obtained from the panning of gold bearing black sands, about forty miles from Fort Jones, Siskiyou Co., Cal., were sent to the writer by Dr. C. S. Cowan, for identification. The crystals are transparent, and vary from very pale to deep wine in color, resembling quite strongly wine-colored topaz crystals in general appearance. They range from two to five millimeters in size and are about as long as they are broad. The faces are exceptionally bright and perfect, and yield the most perfect reflections.

The forms observed are:—

$a(100)$	$e(101)$
$m(110)$	$p(111)$
$x(311)$	$z(511)$

The measurements made with the reflecting goniometer were as follows:—

	Measured.	Calculated.
$a : x = (100) : (311)$	31° 43′	31° 43′
$a : z = (100) : (511)$	20° 21′	20° 25′

	Measured.	Calculated.
$a : p = (100) : (111)$	61° 40′	61° 40′
$a : e = (100) : (101)$	57° 22′	57° 22′
$a : m = (100) : (110)$	45° 0′	45° 0′
$m : p = (110) : (111)$	47° 50′	47° 50′
$m : x = (110) : (311)$	36° 41′	36° 41′
$m : e = (110) : (101)$	63° 36′	63° 35′
$p : x = (111) : (311)$	29° 57′	29° 57′
$p : e = (111) : (101)$	28° 20′	28° 20′
$c : e = (101) : (011)$	44° 50′	44° 50′
$x : p = (311) : (1\bar{1}0)$	53° 19′	53° 19′
$x : z = (311) : (511)$	11° 18′	11° 22′

The crystals are remarkable for the large development of the ditetragonal pyramid $x(311)$. It is present on all of the crystals, with the faces nearly equal in size those of $a(100)$ and $e(101)$, these three forms predominating. The general habit and relative size of the forms on the crystals are shown in Figure 5, Pl. 9.

A few of the crystals are water-worn, but the majority have their edges very little roughened or their faces marred. The nearly colorless ones are evidently bleached out, as very little heating of the deep wine crystals produces perfectly clear colorless ones.

The original source of the crystals is unknown to the writer, but, judging from the very slight abrasion they have undergone, they have not been transported a great distance.

III. ESMERALDAITE, A NEW HYDROUS SESQUIOXIDE OF IRON FROM ESMERALDA COUNTY, NEVADA.

Specimens of yellowish-brown earthy material containing small pod-shaped masses of a coal black mineral were sent to the department, some years ago, by Mr. W. H. Shockley, from Esmeralda County, Nevada, and analyses have lately been made of the material by Mr. Schaller.

The brown earthy mass is apparently a highly siliceous limonite containing about 14% Fe_2O_3. The black mineral proves to be a ferric oxide with a high percentage of water and with considerable impurities, notably of phosphorus and aluminum. It has been deposited in the cavities of the earthy mass in a solid amorphous

form very similar to opal deposits. The mineral has a coal black color and a bright vitreous luster, showing an occasional iridescent tarnish. It is translucent on its edges, and thin splinters are yellowish-red in transmitted light. The mineral is exceedingly brittle, and breaks with a conchoidal fracture. It has a hardness of 2.5 and a yellowish-brown streak. It is easily and completely soluble in acids, but infusible, becoming magnetic after ignition.

The average of several analyses of the black mineral showed the composition:—

	Per cent.
Fe_2O_3	56.14
Al_2O_3	5.77
CaO	3.35
P_2O_5	4.49
Organic	1.37
SiO_2	2.05
H_2O at 110° C.	15.94
H_2O over 110° C	10.24
	99.35

The specific gravity is 2.578.

When the mineral was heated over a blast lamp, the ferric oxide became somewhat reduced, owing probably to the presence of some organic matter. As the amount of water obtained by direct weighing was 26.18%, and by ignition at low red heat without any apparent reduction was 27.55%, the difference, 1.37%, probably represents this organic matter. The water expelled at 110° C. was readily reabsorbed by the pulverized mineral, and since the mineral is a solid homogeneous body, all the water driven off may well be considered as belonging to the composition of the mineral.

It is impossible to state in just what condition the phosphorus and other oxides exist in the substance, so, if we reckon them as impurities and consider the mineral as a simple hydrous sesquioxide of iron, the analysis reduced to 100% becomes:—

	Per cent.	Ratio.	
Fe_2O_3	68.20	4.61	1
H_2O	31.80	17.66	4.14

This gives a ratio of ferric oxide to water of approximately 1:4, corresponding to the formula Fe_2O_3 $4H_2O$.

The mineral resembles limonite in the nature of its impurities and color of its powder, but differs from it radically in the amount of water, low specific gravity, hardness, and its clearly amorphous, glassy nature. The analysis approaches more closely to those of limnite. It is the same kind of deposit and probably resembles in appearance melanosiderite, described by J. P. Cooke,* but there is no question about the mineral being an oxide.

The mineral has such distinctive characteristics that the name *esmeraldaite* is proposed, to distinguish it from the other hydrous ferric oxides.

Portions of the deposits, while still retaining the structure and general characteristics of the black mineral, have by some change lost the bright vitreous luster and become dull and dark brown in color. A partial analysis of this brown variety gave Fe_2O_3 50.26% and H_2O 22.70%. This shows the relative proportion of ferric oxide to water to be about the same as in the black mineral; but a greater amount of impurities is indicated.

IV. COQUIMBITE, FROM THE REDINGTON MINE, KNOXVILLE, CAL.

A green ferric sulphate, which was found in the Redington mercury mine in a wet, mushy condition, became quite compact and crystalline after a natural drying for several months in the air, and the compact material has been recently analyzed by Mr. Schaller.

The color of the sulphate is light yellowish-green with patches of dark green, and the structure is distinctly fine granular. Under the microscope the mass is seen to consist of minute, doubly-refracting plates and grains which resemble rhombohedral plates in form, but the small size of the individual grains prevented any definite conclusions regarding the crystal system. An attempt to recrystallize the mineral produced only a highly deliquescent salt.

In its various properties the mineral is similar to coquimbite. The hardness of the more compact portion is about 2–2.5. The

*J. P. Cooke, Trans. Amer. Acad. Arts and Sciences, 1875, **10**, 451.

taste is strongly astringent and the water obtained in a closed tube is strongly acid. The mineral is soluble in water, and when the solution is heated, a precipitate of red sesquioxide of iron is formed. It is easily and completely soluble in dilute acids.

Two analyses of the mineral gave as its composition:—

	Per cent.	Per cent.	Mean analysis Per cent.	Ratio.	
Fe_2O_3	12.95	13.03	12.99	.812	
Al_2O_3	7.30	7.58	7.44	.729	
SO_3	38.44	37.63	38.04	4.755	
H_2O at 110° C.	23.32	24.13	23.72	13.179	20.796
H_2O, ignition	13.40	14.02	13.71	7.617	
FeO	0.13	0.14	0.13		
SiO_2	0.17	0.24	0.21		
Na_2O	1.68	1.68	1.68		
MgO	1.09	1.14	1.09		
	98.48	99.59	99.04		

The analyses show that the mineral is essentially a hydrous sulphate of iron and aluminum, the other oxides present being simply impurities. In calculating a formula for the mineral, the only difficulty that arises is with respect to the amount of water which really forms a part of the mineral's composition. It is highly probable, from the fact that the material has been gradually drying out, that the water expelled at 110° C. was partly that of crystallization and partly occluded.

The ratio obtained from the mean analysis corresponds very nearly to the formula $Fe_2(SO_4)_3$ $Al_2(SO_4)_3$ $27H_2O$. Assuming all the H_2O present as water of crystallization, then our substance might be viewed as a mixture of the two minerals, coquimbite, $Fe_2(SO_4)_3+9H_2O$, and alunogen, $Al_2(SO_4)_3+18H_2O$.

Such a mixture would require the following percentages of the oxides:—

		Mean analysis reduced to 100%.
Fe_2O_3	13.03	13.54
Al_2O_3	8.30	7.76
SO_3	39.10	39.67
H_2O	39.57	39.03
	100	100

The calculated percentages for the mixture agree fairly well with the reduced analysis, but there is nothing to indicate that the substance is other than homogeneous. In view of this fact and the high probability of occluded water in the analyses, the writer is inclined to the belief that the mineral is wholly coquimbite, since it possesses properties so similar. In this case, about one-half of the iron has been replaced by aluminum, and about 10 per cent of the water must be regarded as occluded.

The analysis, calculated as a pure ferric sulphate containing only the amount of water necessary for coquimbite, becomes:—

		Required for coquimbite $Fe_2(SO_4)_3+9H_2O$
Fe_2O_3	27.99	28.47
SO_3	43.18	42.70
H_2O	28.83	28.83
	100	100

The mineral constitutes an additional member of an undoubted series of sulphates, and mixtures of sulphates, in the Redington Mine, resulting from the decomposition of the abundant marcasite.

Melville and Lindgren* have reported the occurrence of copiapite, Knoxvillite, and Redingtonite from this mine, the analyses of which minerals differ quite materially from the coquimbite, no chromium being found in the coquimbite.

V. ALTAITE CRYSTALS, FROM SAWMILL FLAT, TUOLUMNE COUNTY, CALIFORNIA.

Some delicate little specimens of gold, cementing minute, dark gray isometric crystals, came from a pocket in the Birney pocket mine, near Sawmill Flat, Tuolumne County, Cal., and an analysis of these crystals by Mr. W. J. Sharwood, to whom the writer is indebted for these notes, shows them to be altaite crystals.

The gold and altaite are intimately associated, some of the crystals having a gold coating, while the majority are perched on the ends of gold stems or wires.

The crystals are from 1–2 mm. in diameter, and are mainly

*Melville and Lindgren, Mineralogy of the Pacific Coast, 1890, Bull. 61, U. S. Geological Survey.

combinations of the octahedron and cube, the former predominating. Many of them, however, have the cubo-octahedral edges beveled by narrow faces which measurements show is the trapezohedron, $\beta(322)$. The measurements with the reflecting goniometer were:—

	Measured.	Calculated.
$(111):(1\bar{1}1)$	70° 31′	70° 32′
$(111):(11\bar{1})$	109° 24′	109° 28′
$(111):(322)$	11° 22′	11° 25′

The typical appearance of these crystals is illustrated in Figure 6, Pl. 9.

The analysis shows the composition of the crystals to be as follows:—

	Per cent.	Calculated for Pb Te. Per cent.
Te	32.5	37.7
Pb	65	62.3
Ag	Traces up to 0.1	
An	None	
Fe	Trace	
Se	"	
S	"	

In one portion gold to the amount of 6 per cent was found, but this was doubtless due to a mechanical admixture of the intimately-associated gold, as the purer material gave no test for gold. The analysis differs somewhat from the theoretical composition of altaite, yet it is sufficiently near to indicate that the crystals are altaite.

Some of the gold is in the form of highly-distorted octahedrons, and partial analyses of these crystals gave 91.2 per cent to 94.2 per cent gold.

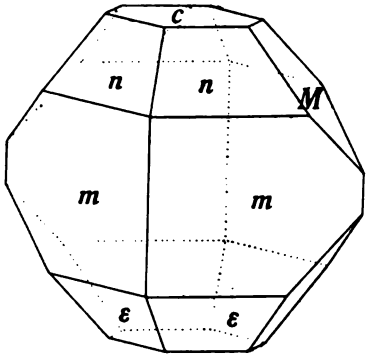
Crystals of altaite are exceedingly rare in occurrence, and only the cube form has heretofore been observed.

Massive altaite showing cubic cleavage occurs at the Stanislaus Mine, Calaveras County, and has also been reported from the Golden Rule Mine, Tuolumne County, by Genth.*

University of California,
October, 1901.

*F. A. Genth, Amer. Jour. Science, 1868, **45**, 312.

1



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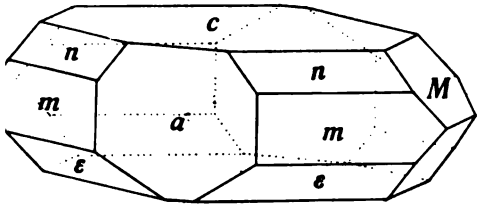

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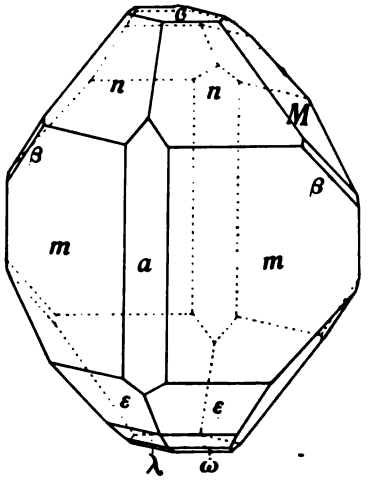

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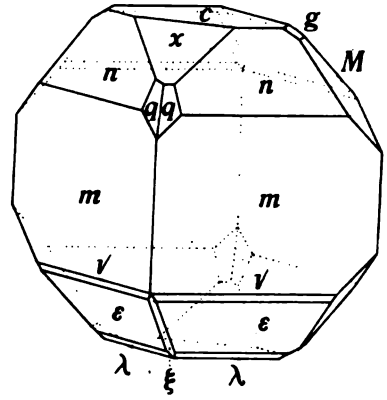

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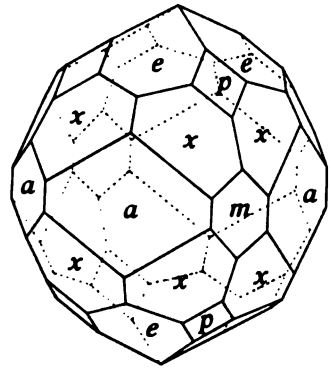

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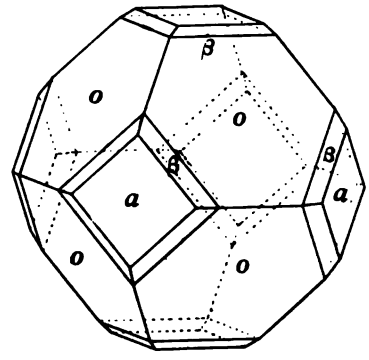

DATOLITE, 1-4: ZIRCON, 5; ALTAITE, 6.

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CONTRIBUTION TO THE MINERALOGY OF CALIFORNIA.

BY

WALTER C. BLASDALE.

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INTRODUCTION.

Comparatively few of the mineral species which are found in the Coast Ranges of California have been submitted to detailed investigation. The desirability of definite and complete knowledge of the more widely distributed species, especially those which are important rock constituents, is self-evident; it is essential for comparison and correlation with similar minerals from other regions, and is also necessary for any comprehensive study of the relations

which the various rock masses bear to each other. At the suggestion of Professor Lawson, to whom I would also acknowledge many obligations for assistance, the work which is here outlined was undertaken, its specific object being to determine more definitely the important physical and chemical properties of some of the most striking species of local occurrence. The specimens used in the investigation were all obtained from either one of two localities in the Berkeley Hills immediately east of the Bay of San Francisco, one (designated as locality A) near the northern limits of the town of Berkeley and the other (designated as locality B) not far from, and to the south of, the village of San Pablo.

A GREEN HORNBLENDE.

Occurrence.—This mineral is found in both the localities cited. At the former station it occurs in the form of loose boulders, within an area of schists and serpentine. These boulders are from ten to thirty centimeters in diameter, and consist of coarsely crystalline, compact masses of the green mineral, the interstices between the crystals being filled with either talc or chlorite, only one of the associated minerals being present in the same boulder. In some instances the boulders are composed of pure hornblende, and in no instance do the associated mineral form any considerable percentage of the entire mass. The second occurrence of the mineral presents essentially the same features. The boulders are here distributed over a considerable area characterized by the presence of crystalline schists, of serpentine, and of various alteration products of the latter. Though the majority of the boulders are small and present only rounded and polished surfaces, masses of angular form whose longest dimension exceeds 75 centimeters were several times observed. As in the former locality, they were in all cases coarsely crystalline, the individuals often attaining ten centimeters in length and several millimeters in their longer diameter; chlorite was here the more common associate. Frequently indications of a schistose structure were shown by the manner in which the boulders cleave on breaking; in other instances definite crystal centers could be recognized, but in many cases no especial orientation of the constituent crystals was to be observed.

General Description.—For the detailed study of the mineral two of its occurrences were selected, a boulder containing talc as the associated mineral from locality A and a portion of the mass from a blue hornblende rock of locality B. The long lath-shaped crystals composing the greater part of the boulder were frequently imperfect and distorted, but from the interior of it a few well-developed crystals were obtained. These showed only two planes, the prism and the clinopinacoid. The inclination of the prismatic faces (110) and ($1\bar{1}0$) was found to be 54° 10′, though the reflections obtained were poor and only admitted of approximate measurement. Nearly all the crystals showed indications of the action of pressure or other distorting factors. Those on the periphery were frequently bent through angles of 5° to 20°, sometimes abruptly, but more often to a more curvilinear outline. Microscopic cracks, commonly at right angles to the prismatic axis of the crystal, were scarcely ever absent, and were often so abundant as to render even the thinnest crystals more or less opaque. The color of the mineral is uniformly of a light emerald green, and crystals free from the above-noted feature were perfectly transparent. Inclusions were in no case observed. Two sets of cleavage planes parallel to the prismatic faces were strongly developed. The specific gravity is 3.116, in which respect it corresponds closely with the mineral actinolite.

Optical Properties.—The determination of the optical features of the mineral is rendered difficult on account of the microscopic cracks previously noted. A section cut parallel to (010) when examined for extinction with a Bertrand ocular gave as the average of seven measurements, 14° 34′. Des Cloizeaux, working with a St. Gothard actinolite obtained the value 15°, and Levy and Lacroix* obtained the same value for Zillerthal actinolite. The direction of extinction which makes the smaller angle with the cleavage trace in a section parallel to (010) was shown by means of a quartz wedge to be the position of least elasticity. The same section examined in convergent polarized light gave no figure, while a section parallel to (100) showed the emergence of an optic

* Comptes Rendu, Tome 106, p. 777.

axis. Hence the orientation of the axis of least elasticity must be $\mathfrak{c}:c=14°\ 34'$.

In the absence of terminal planes it is impossible to determine whether $\mathfrak{c}$ divides the acute or obtuse angle between a and c.

The indices of refraction of the different rays could not be determined satisfactorily, owing to the nature of the material. Approximate results were obtained by the method of Duc de Chaulnes, the figures being for α 1.6267, for γ 1.6529, giving .0262 as the strength of double refraction. Compared with measurements of α and γ on Zillerthal actinolite by Levy and Le Croix* these results are high, though the strength of double refraction is about the same.

Pleochroism is pronounced. The color of the $\mathfrak{c}$ ray is bluish green, of $\mathfrak{b}$ a lighter shade of green, and of $\mathfrak{b}$ a yellow-green.

The absorption formula is $\mathfrak{c}>\mathfrak{b}>\mathfrak{b}$. Sections parallel to the vertical zone sometimes show unequal absorption. A similar phenomenon was noted by Palache† in crossite, and by Daly‡ in philipstadite.

Cohesional Properties.—The study of the cohesional properties of minerals has been applied to the members of the hornblende series with marked success by Daly.‖ The material under consideration yielded only prismatic planes, which were of sufficient dimensions to admit of a satisfactory application of this method. Also the microscopic cracks previously noted rendered it difficult to obtain crystals which did not give rise to abnormal results, since solvent action took place along these planes with great rapidity. The crystals, or cleavage flakes, were etched with strong hydrofluoric acid at the temperature of boiling water for periods varying from one to five minutes. Examination of the pits thus produced was made with transmitted light, using a magnification of about two hundred diameters. Essentially the same results were obtained from crystals as from cleavage flakes, and no differences were observed in the behavior of the actinolite from the two localities.

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* Comptes Rendu, Tome 106, p. 777.

† This Bulletin, vol. 1, p. 190.

‡ Proc. Am. Acad. Arts and Sciences, vol. 34, p. 434.

‖ Proc. Am. Acad. Arts and Sciences, vol. 34, p. 374.

The general features of the etch-pits thus obtained are shown in the accompanying figures. No. 1 represents a partly- and No. 2 a fully-developed pit, No. 3 represents a group of pits one of which has attained its perfected form. The essential character of all the normally-developed pits consists of three curved faces,

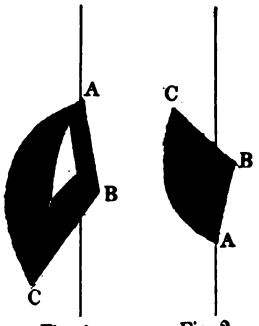

Fig. 1.

Fig. 2

Fig. 3.

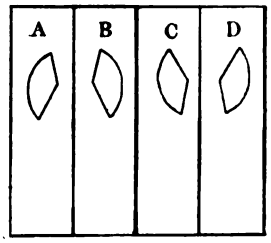

Fig. 4.

which form a solid angle near the center of the pit, and intersect the crystal plane in three lines, two of the latter being straight or very nearly so, and of nearly equal length, the third forming a long bow-shaped curve. One of the straight lines forms a slight angle with the prismatic cleavage trace; the other, commonly the longer, is at a considerable angle with it. In general the figures closely resemble those obtained with normal actinolite by Daly, the variations, such as are observed in the curvature of the longest line of the figure, being no greater than those obtained in etching different crystals from the same locality. For the angle between the line AB and the cleavage trace Daly obtained values varying from $-2°$ to $+12°$ according to the stage of development of the figure; the present material gave members ranging from 4° to 8° 15′; for the angle between AC and the cleavage trace Daly obtained from 10° to 16°, while the material under consideration gave from 10° to 16° 36′.

The absence of terminal planes in actinolite crystals renders it impossible to correlate with certainty the position assumed by the etch-figures with reference to the crystallographic orientation. A study of the positions assumed by the figures on the four prismatic planes gave results in accord with the orientation adopted by Daly.

Figure 4 shows the apparent positions, as viewed under the microscope, of the figures on the four faces of a crystal, the greater of the prismatic angles lying between A:B and C:D. It is to be noted that the most acute angle of the figure points either up or down according to whether the face is to the front or back (normal orientation) of the crystal. In this respect the figures agree with Daly's statement that the "claw" of the figure points towards the positive hemipyramids. Daly deduces the latter statement from an analogy between the etch-figures of actinolite and those of other varieties of hornblendes of known orientation, and Wright* deduces the same relation from a study of a hornblende from Vesuvius. Accepting the above as the correct correlation, the true orientation of the four planes would be as follows: A=($1\bar{1}0$), B=(110), C=($\bar{1}10$), D=($\bar{1}\bar{1}0$). It is to be noted, however, that these results do not represent the actual position of the figures on the crystal, since in my own figures, and presumably in those of Daly and Wright, no account is taken of the fact that right and left are interchanged.

Chemical Properties.—The mineral is scarcely affected by strong hydrochloric acid and was only partially decomposed by heating in a sealed tube with boiling sulphuric acid. Analyses of two carefully-selected and inclusion-free samples are given in Table I. Sample No. 1 was obtained from the boulder that furnished the material used in the determination of the optical properties; No. 2, from a boulder collected at locality B. The two analyses show in their general features no marked variations, the differences being such as might easily arise from the substitution of isomorphous bases. Compared with typical actinolite from Zillerthal (see analysis No. 3) and with other analyses of glassy actinolite (see analyses 4, 5, and 6) there is still a general agreement, the noteworthy differences being the lower percentage of magnesia, and the presence of considerable amounts of alumina, of the alkalies, and of combined water. The low percentage of magnesia is largely compensated for by the higher content of ferrous oxide and lime. The alumina appears to be higher than in any of the analyses of this

*Tschermak's Min. u. Pet. Mitth. Band 19, S. 317.

TABLE No. I.

Analyses of Green Hornblendes.

	1	2	3	4	5	6
SiO_2	55.21	55.56	55.50	55.00	55.01	56.33
Al_2O_3	3.45	2.05	.....	1.51	1.69	1.67
Fe_2O_3	.....	.....	.....	.99	.56	.....
FeO	7.49	5 97	6.25	3.46	3.46	4.30
MgO	18.97	19.45	22.56	23.31	23.85	24.00
CaO	10.50	12.13	13.46	10.38	13.60	10.67
Na_2O	2.45	1.94	.....	1.10	.51	.....
K_2O	.....	.30	.....	1.12	.38	.....
H_2O at 100°	.....	.....	.....	.....	.....	.....
H_2O above 100°	1.75	2.58	1.29	2.90	1.02	1.03
MnO	.....	.....	.....	.31	.48	.....
	99.82	99.98	99.06	100.08	100.56	98.00

1. Actinolite from Berkeley, California.
2. Actinolite from San Pablo, California.
3. Actinolite from Zillerthal, Rammelsberg, Mineral Chemie, S. 471.
4. Actinolite from Scotland, Heddle, Trans. Roy. Soc. Edinburgh, vol. 28, p. 508.
5. "Hornblende" from Russia, Michaelson, Journ. für Prakt. Chemie, Band 91, S. 221.
6. Actinolite from Concord, Mass., Seybert, Am. Journ. Science, vol. 6, p. 333.

TABLE No. II.

Calculations Leading to the Formula of the Green Hornblende.

Analysis 1.	Elementary Composition.		Atomic Quotient.	Atomic Ratio.	Analysis 2.	Elementary Composition.		Atomic Quotient.	Atomic Ratio.
SiO_2 55.21	Si	25.96	.9211	25.00	SiO_2 55.56	Si	26.12	.9270	25.00
Al_2O_3 3.45	Al	1.83	.0680	1.84	Al_2O_3 2.05	Al	1.09	.0404	1.09
FeO 7.49	Fe	5.83	.1048	2.84	FeO 5.97	Fe	4.64	.0835	2.25
CoO 10.50	Ca	7.50	.1886	5.12	CoO 12.13	Ca	8.67	.2180	5.88
MgO 18.97	Mg	11.43	.4744	12.87	MgO 19.45	Mg	11.72	.4863	13.11
Na_2O 2.45	Na	1.82	.0795	2.16	Na_2O 1.94	Na	1.44	.0629	1.70
K_2O	.....		.....	.....	K_2O .30	K	.25	.0064	.02
H_2O 1.75	H	.20	.20	5.43	H_2O 2.58	H	.29	.29	7.80
....	O	45.26	2.85	77.36	.....	O	45.76	2.88	77.66

mineral thus far reported, though it does not greatly exceed the total sesquioxide content reported in analysis No. 4. The presence of alkalies, in amounts sufficient to be considered as important

constituents of actinolite, seems to be abnormal, but as a matter of fact many of the more recent and carefully executed analyses show that these bases are commonly present. A similar remark might be made with reference to the water content. That the water here reported is constitutional can not be questioned since hygroscopic water was determined by drying at 100° and the material experienced no appreciable loss between 100° and 350°.

In Table II are tabulated the results of the calculations leading to the determination of the formula of the mineral. It will be noted at once that the oxygen is but slightly in excess of that corresponding to a metasilicate ratio. Most of the theories for the constitution of the hornblende group ignore entirely the presence of constitutional water, which fact probably rests ultimately upon the decision of Rammelsberg* that this is only to be regarded as the beginning of an alteration. In the present material, and apparently the same remark would apply to all of the other analyses of actinolite reported in Table I, no indications of such alteration could be detected.

The fact that water is reported in many other members of the group, and that it has been admitted as an important constituent of the closely-related pyroxene pectolite, would seem to demand that it should be included in any structural theory of the group. Further difficulties in applying the structural theories of Rammelsberg and Tschermak appear with reference to the sesquioxides and alkalies. According to Tschermak's theory of the hornblende group, the alkalies must be accompanied by equivalent amounts of sesquioxides, hence any attempt to explain the structure of the present mineral as a mixture of the glaucophane molecule and the actinolite molecule would fail, since the alkali content in both analyses exceeds the sesquioxide content. The theory proposed by Clarke† might be applied with a greater degree of success since it admits the equivalence of K, Na, H, AlO, Fe'''O. Representing this group of symbols by R', the dyad group by R'', and by X a mixture of Si_3O_8 and SiO_4 in nearly equivalent proportions, the first analysis may be summed up as

* Poggendorff's Annalen, Band 103, S. 435.

† Bull. 125 U. S. Geol. Survey, p. 94.

$R''_{29.83}\ X_{12.5}\ R'_{9.43}$, and the second as $R_{21.24}\ X_{12.5}\ R'_{10.61}$. The composition of the two samples may then be represented thus:—

I

$$\left.\begin{matrix}2.36\ R''_3X_2R'_4\\ 4.03\ R''_4X_2\end{matrix}\right\} = R''_{29.84}\ X_{12.80}\ R'_{9.44}$$

II

$$\left.\begin{matrix}2.65\ R''X_2R'_4\\ 3.90\ R'_4X_2\end{matrix}\right\} = R''_{21.24}\ X_{13.10}\ R'_{10.60}$$

Finally it may be stated that in crystallization, in optical and in other physical properties, the mineral presents no remarkable features, and its differences of chemical composition are not sufficient to warrant separation from the mineral actinolite.

A BLUE HORNBLENDE.

Hornblendes of a deep blue color are not uncommon in the rocks of the Coast Ranges. One of these was considered by Lacroix* and later by Becker† to be normal glaucophane; a second, the only one fully described up to the present time, was shown by Palache to be identical with a species from Custer County, Colorado, and was named by him crossite. The material used by Palache was obtained from a locality but a few miles to the north of Berkeley, about midway between the two localities here considered, but, as the sequel shows, differs from the mineral here described.

Occurrence.—Unlike the actinolite, the blue hornblende is found in rock masses of considerable extent, which must be regarded as one of the important rock formations of this range of hills. Good exposures are not plentiful, but their extent and the variety of facies they present is evinced by the abundance of float strewn over certain areas of the hill slopes. This material often assumes the form of boulders, not dissimilar to those of the actinolite, but commonly consists of more or less angular masses, most of which show a schistose structure. Many specimens consist wholly of the pure mineral, the crystals varying greatly in size in different specimens, and the whole forming an exceedingly hard, compact mass. Other specimens show mixtures of the mineral with albite, chlorite, garnet, or actinolite, mica, and quartz. One large detached rock

* Report Cal. State Mineralogist (1884), p. 182.

† Monograph XIII, U. S. Geol. Survey, p. 76.

mass, some twenty feet long by six in thickness and five in width, illustrates the occurrence of the mineral *in situ*. This formed an exceedingly compact rock, composed for the most part of the relatively large crystals of the blue hornblende arranged without any common orientation and associated with garnet, chlorite, actinolite, titanite, and albite. The chlorite and actinolite were frequently localized in certain portions of the rock, forming areas of as much as ten centimeters in thickness; the other minerals were more generally distributed through the entire mass. It was from this aggregate that the specimen of actinolite already described was obtained; it also furnished one of the specimens used for the study of the blue hornblende and of the chlorite described later on.

General Description.—Weathered surfaces of the rock were lusterless and of a dark gray color, but freshly-exposed portions presented a blue-black color, and showed no evidences of decomposition. Associated with the hornblende were crystals and angular fragments of titanite, often several millimeters in length. The latter mineral, however, was badly decomposed, consisting of a light yellow opaque mass, though the inner portions of some of the larger crystals were transparent and of a characteristic reddish-yellow color. Sections of the rock showed a complex intergrowth of the hornblende crystals, together with small amounts of actinolite, chlorite, and titanite. The hornblende appeared in either rectangular or rhombic areas, and were easily distinguished by their strong pleochroism. Inclusions of titanite were sometimes observed. The second specimen examined was a compact polished boulder, composed of fine needle-shaped crystals arranged with their longest axes in approximately the same plane. Sections of this showed the entire absence of other minerals either as inclusions or as intergrowths.

From the first specimen a few perfect, columnar crystals, some three to five millimeters in cross section and two centimeters in length, which had partially weathered out from the rock mass, were obtained. These presented only prismatic and clinopinacoidal faces. Though too dull to give good reflections, an approximate measurement of the prismatic angle gave the value 125° 14′. For the mineral crossite, Palache obtained the value 126° 6′, and for

typical glaucophane Bodewig found 124° 51′. Strongly-developed prismatic cleavages are shown in all sections of the mineral.

Optical Properties.—From some of the most perfect crystals sections were cut parallel, or as nearly so as the nature of the material would permit, to the clino- and orthopinacoids. The former extinguished light at an angle of 8° with the cleavage trace and in convergent light gave no interference figure. This position was shown by the use of a quarter-undulation mica plate and also of a plate of gypsum, both of known orientation, to be the direction of least elasticity, in which respect the mineral differs from crossite and agrees with glaucophane, though the extinction angle is greater by two degrees than in any specimen of that mineral which has been examined thus far. Sections cut parallel to the orthopinacoid gave parallel extinction, and with convergent light gave only a broad brush of interference colors. The optical orientation is, therefore, the same as that found in the majority of hornblendes, that is, $\mathfrak{c}:c = 8°$, though in the absence of terminal crystallographic planes the exact position of $\mathfrak{c}$ can not be determined. The pleochroism is the most pronounced optical feature of the mineral and furnishes the most valuable criterion for its identification. The color of the $\mathfrak{c}$ ray is bright sky blue to deep blue, of $\mathfrak{b}$ purple to violet, and of $\mathfrak{a}$ colorless, or a very faint yellow. In these respects the mineral closely resembles glaucophane, but differs from crossite. In some crystals certain localized areas presented a light green color, probably due to the presence of actinolite, though no very definite line of separation from the main portion of the crystal could be distinguished.

Chemical Properties.—A portion of the first-described specimen was crushed in an agate mortar, and treated with hydrochloric acid, washed, and dried, and that portion which passed through an eighty- but was retained by a one-hundred mesh sieve, separated from the remaining titanite by means of Klein's solution. The purified material had a specific gravity of 3.119. The second specimen was ground for analysis without further preparation; it gave a specific gravity of 3.116. The finely-ground material, which is of a blue-gray color, fused readily with the formation of a dark glass, and was scarcely attacked by strong acids even after long boiling.

TABLE No. III.

Analyses of Blue Hornblendes.

	1	2	3	4	5	6	7	8
SiO_2	54.52	52.39	57.67	55.64	56.49	57.81	55.02	55.06
Al_2O_3	9.25	11.29	11.07	15.11	12.23	12.03	4.75	.49
Fe_2O_3	4.44	3.74	3.20	3.08	.....	2.17	10.91	15.48
FeO	9.81	9.13	9.68	6.85	10.91	5.78	9.46	7.40
MgO	10.33	11.37	9.85	7.80	7.97	13.07	9.30	11.49
CaO	1.98	3.03	.95	2.40	2.25	2.20	2.38	.98
Na_2O	7.56	6.14	6.80	9.34	9.28	7.33	7.62	6.38
K_2O	.16	trace	.42	.....	.....	.....	.27	.80
H_2O at 100°	.....	.....	.12	.....	.....	.....	undet	.....
H_2O above 100°	1.78	2.57	.36	.....	.....	.....	.....	1.98
TiO_2	.39	.14	.....	.....	.....	.....	.....	.....
MnO	.46	trace	.06	.56	.50	.....	trace	.....
	100.68	99.80	100.18	100.78	99.63	100.39	99.70	100.06

1. Blue hornblende from rock, San Pablo, California.
2. Blue hornblende from boulder, San Pablo, California.
3. Glaucophane from Syra, Washington, Am. Journ. of Science [4], 40, vol. 11, p. 40.
4. Glaucophane from Syra, Luedecke, Zeit. d. Deut. Geol. Gesellsch, Band 28, S. 252.
5. Glaucophane from Syra, Schnedermann, Journ. für Prakt. Chemie, Band 34, S. 238.
6. Glaucophane from Zermatt, Bodewig, Pogg. Annalen., Band 158, S. 228.
7. Crossite from Berkeley, this Bulletin, vol. 1, p. 188.
8. Glaucophane from Syra (Rhodus), Toullon, Sitzb. Akad. Wein., Band 100, S. 172.

TABLE No. IV.

Calculations Leading to the Formula of the Blue Hornblende.

Analysis 1.	Elementary Composition.	Atomic Quotient.	Atomic Ratio.	Analysis 2.	Elementary Composition.	Atomic Quotient.	Atomic Ratio.
SiO_2 54.52	Si 25.64	.9098	25.	SiO_2 52.39	Si 24.63	.8740	25.
Al_2O_3 9.25	Al 4.91	.1824	5.01	Al_2O_3 11.29	Al 5.99	.2225	6.36
Fe_2O_3 4.44	Fe 3.11	.0559	.15	Fe_2O_3 3.74	Fe 2.62	.0471	1.35
FeO 9.81	Fe 7.63	.1372	3.76	FeO 9.13	Fe 7.10	.1276	3.65
MgO 10.33	Mg 6.23	.2585	7.10	MgO 11.37	Mg 6.85	.2842	8.13
CaO 1.98	Ca 1.41	.0354	.97	CaO 3.03	Ca 2.16	.0543	1.55
Na_2O 7.56	Na 5.61	.2452	6.73	Na_2O 6.14	Na 4.56	.1993	5.70
K_2O .16	K .13	.0033	.09	K_2O trace	.....	.....	.....
H_2O 1.78	H .20	.2000	5.49	H_2O 2.57	H .29	.2900	8.29
TiO_2 .39	Ti .24	.0050	.14	TiO_2 .14	Ti .08	.0017	.05
MnO .46	Mn .36	.0066	.18	MnO trace	.....	.....	.....
....	O 44.53	2.8042	77.00	....	O 45.72	2.879	80.73

The results of the analyses of the two specimens are given in the first two columns of Table III; for comparison five analyses of glaucophane, four from the type locality of Syra, and one from Zermat, also the analysis of crossite, are included in the same table. In both of the analyses here reported the close relationship of the mineral to typical glaucophane is apparent. The only features worthy of especial note are the relatively large amounts of combined water and titanium. The latter element is easily accounted for in the first analysis by its inclusions; probably these were also present in the second specimen but escaped detection. Apparently the water is due to hydrogen which displaces the alkali metals to a certain extent as in the actinolite. Even larger percentages of water (namely four) are reported by Barrois.* Compared with the analysis of crossite, striking differences of the sesquioxide content are worthy of note. From a chemical standpoint the most important difference between the two minerals consists in the substitution of nearly equivalent amounts of ferric oxide for alumina. Presumably this difference is directly connected with the difference in the optical orientation, and though the data is too incomplete to be conclusive, there are indications that there is a direct connection between the position of the acute bisectrix and the relative amounts of ferric oxide and alumina. In this connection, analysis No. 8, representing a variety of glaucophane from Syra (Rhodus), is of especial interest; the difference in the relative percentage of the sesquioxides is here even more strongly accentuated, but, unfortunately, no account of the optical properties of this variety appear to have been published.

In Table IV are given the calculations leading to the formula of the mineral. It will be noted that the ratio of oxygen to silicon is in both analyses slightly greater than corresponds to a metasilicate. If, as in the actinolite, we represent the diad metals by R″, the elements H, Na, K, AlO, Fe‴O by R′, and by X a mixture of Si_3O_4 and SiO_4 in nearly equivalent proportions, but with a slight excess of SiO_4, the composition of the two samples would correspond to the formulas $R''_{12\cdot01}\ X_{12\cdot5}\ R'_{16\cdot47}$ and $R''_{13\cdot35}$

* Barrois, Comptes Rendu, Tome 103, p. 221.

$X_{12.5}$ $R'_{21.70}$, which are fairly well represented by the following formulæ:—

$$\text{I}\qquad 4.5\left\{\begin{matrix}R''_3X_2R'_2\\ R''_2X_2R'_4\end{matrix}\right\}=R''_{12}X_{11}R'_{20}$$

$$\text{II}\qquad \left\{\begin{matrix}R''_3X_2R'_2\\ 5R''_2X_2R'_4\end{matrix}\right\}=R''_{13}X_{12}R'_{22}$$

TREMOLITE.

At a single point in locality B contact between the schist and serpentine was observed. Between the beds of dark-colored serpentine and schist here found, a thin layer of a light-colored fibrous mineral was noted. Its contact with the serpentine was distinguished by a series of curved and moulded surfaces, clearly indicating the action of heavy pressure at this point. On the other hand, the mineral was associated with actinolite and glaucophane, and intergrowths of the light-colored mineral and the more coarsely crystalline actinolite were observed.

The pure mineral occurs in masses of fibrous crystals of pure white to light gray-green color, which show a pronounced schistose structure. It is easily crumbled into fine needle-like crystals, which are too small to be studied without magnification, but are

TABLE No. V.

Analyses of Tremolite, Chlorite, and Talc.

	1	2	3	4
SiO_2	56.68	27.38	27.03	56.02
Al_2O_3	1.79	26.15	20.07	9.02
Fe_2O_3	1.70	.78	4.72	1.10
FeO	2.23	12.70	16.47	5.14
MgO	19.35	18.92	18.90	24.10
CaO	15.80	.....	.....	.60
Na_2O	.....	1.15	.72	.....
K_2O	.....	.....	1.22	.....
H_2O at 100°	.10	1.51	.....	.16
H_2O above 100°	2.25	11.44	11.78	4.34
	99.90	100.03	100.91	100.48

1. Tremolite from San Pablo, California.
2. Prochlorite from San Pablo, California.
3. Prochlorite from Austria, Vuylsteke, Tscherm. Min. Mitth, N. F., Band 12, S. 34.
4. Talc from San Pablo, California.

then easily shown to be lacking in definite crystallographic planes. Many of these extinguished light parallel to their longest axis, but others gave extinction angles of as much as 4°. The specific gravity of some of the separated crystals was found to be 3.986. The composition of this mineral, as shown by the analysis reported in Table V, is clearly that of tremolite. It presents no unusual features except the rather high percentage of lime and combined water.

CHLORITE.

As previously noted, chlorite is a common associate of the actinolite. Aside from its occurrence in the actinolite boulders, it fills lenticular cavities and veins in the schist; its occurrence in relatively large masses in the glaucophane rock has already been alluded to. Material from the latter source only was examined. It here assumes the form of a scaly-grained dense mass composed of comparatively thick groups of cleavage flakes, the masses being disposed without common orientation. The maximum surface presented by these flakes did not exceed a square centimeter. In some cases the mass parted in such a manner as to give rise to more or less conchoidal surfaces. Crystallographic planes were entirely absent. The cleavage flakes were comparatively transparent, were of a yellow-green to olive-green color, though on exposed portions red stains due to oxidation were very apparent. They extinguished light like an isotropic medium. The specific gravity of a portion weighing about twenty-five grams was found to be 2.792.

Portions from the interior of the mass and as free from oxidation as could be obtained were used for the analysis reported in Table V. The high percentage of silica and the other features of the analysis at once show that it is prochlorite. It may be compared with a specimen of that mineral analyzed by Vuylsteke, which is reported in the fifth column of the table.

TALC.

Talc forms white or apple-green masses filling the interstices between the actinolite crystals and is occasionally found in com-

paratively large masses in the crystalline schist. Though entirely amorphous, some fragments show suggestions of a scaly structure, and in such cases have a mother-of-pearl luster. Material from a boulder obtained from locality A, which was selected as carefully as possible but was probably not absolutely free from very fine actinolite crystals, gave the analysis recorded in the fourth column of Table V. The analysis is remarkable in the comparatively low magnesia and the very high iron and alumina; in fact, in both of the latter figures it exceeds any of the analyses of this mineral of which I have record. The analysis, together with the scaly structure previously alluded to, suggests that the mineral has been derived from chlorite.

DIALLAGE.

This forms a light-colored friable rock which is of rather frequent occurrence in both of the localities here considered, being found both as detached fragments and as groups of massive boulders, the latter probably *in situ*. The specimen examined was obtained from locality B. Structurally the rock is composed entirely of flakes or lamellæ, which often present several square centimeters of surface and are distinguished by their greenish-yellow color and dull, non-lustrous character. True crystallographic planes were never observed, but the lamellæ were often divided by a series of more or less pronounced cleavages into prismatic fragments, sometimes suggesting a fibrous structure. The lamellæ show parallel extinction and with convergent light the eccentric emergence of an optic axis, but a section cut approximately parallel to the prismatic cleavage gave an extinction angle of 7°. It is clear then that the lamellæ represent orthopinacoidal cleavage flakes of a monoclinic pyroxene. A series of transverse partings traverse many of the lamellæ, but there is no visible evidence of alteration, nor were inclusions of other minerals observed. The interference colors are of a high order.

The chemical composition of this substance, as shown by analysis in Table VI, is clearly that of diopside, while its structural features class it as diallage. It shows a remarkably close agreement with a sample of diallage from Scotland, analyzed by Heddle, the

result of which is reported in the same table. The only noteworthy features of the two analyses are the presence of the alkali

TABLE No. VI.

Analyses of Diopside, Serpentine, and Albite.

	1	2	3	4	5
SiO_2	51.91	51.77	49.62	33.66	67.09
Al_2O_3	3.55	2.10	2.97	1.36	20.47
Fe_2O_3	1.30	.....	2.49	.34	.....
FeO	2.65	2.96	2.99	4.80	.....
MgO	16.15	18.46	19.72	38.70	.....
CaO	22.85	22.10	19.14	.48	.24
Na_2O	.56	.58	.60	.98	10.96
K_2O	.....	.63	.....	.....	.....
H_2O at 100°	.21	.....	.....	.24	.27
H_2O above 100°	.86	1.08	2.71	19.70	.59
TiO_2	.10	.....	.....	.....	.....
MnO	.33	.31	.....	trace	.....
	100.47	99.99	100 24	100.26	99.62

1. Diopside (diallage) from San Pablo, California.
2. Diallage from Scotland, Heddle. Trans. Royal Society, Edinburgh, vol. 28, p. 464.
3. Diopside (altered) from San Pablo, California.
4. Serpentinized anthophyllite from San Pablo, California.
5. Albite from San Pablo, California.

metals, and of combined water. The specific gravity of the rock is 3.183. The latter fact, together with the large amount of combined water, probably indicates the beginning of the process of alteration to serpentine.

ALTERED DIALLAGE.

A rather coarse-grained mottled rock, found in relatively large masses *in situ*, especially from locality B. It is easily broken into irregular fragments which present plane or curved surfaces, either light yellowish-green or blue-black in color. Thin sections of the rock show areas of a light greenish-yellow, striated mineral and especially at the angles between these areas veins or masses of a black opaque mineral. Magnification of the light-colored areas shows that this mineral is closely related to the diallage previously

described, the structure, color, transverse partings, and extinction angle all indicating this fact. In some instances, along the cleavage cracks, darker-colored cloudy areas, evidently marking the beginning of alteration, may be observed. The dark-colored areas are resolved into a dark brown somewhat opaque ground mass, and veins composed of grains of magnetite. Apparently they represent those portions in which, on account of the relatively large amount of surface exposed, alteration has been most complete. The blue-black surfaces of the rock are due entirely to veins of magnetite. Specimens collected from the same locality show still further development of the process of serpentinization.

The chemical investigation of the rock, the results of which are recorded in the third analysis of Table VI, confirm the above theory. The decrease in silica and lime and increase of combined water and magnesia, clearly indicate the progress of the process of serpentinization. The specific gravity of the rock is 3.153.

SERPENTINIZED ANTHOPHYLLITE.

This occurs in groups of massive boulders, often rounded but more commonly angular, which outcrop at several points in locality B, often projecting to the height of twenty feet above the prevailing level and suggesting the character of intrusives. The rock is exceedingly tough and compact, and does not fissure readily. The outer surfaces are of an ashy gray color but freshly-exposed portions present yellowish-green cleavage planes or curved surfaces of a light brownish-yellow. Thin flakes of the mineral possess the yellow translucent features characteristic of serpentine, but on the whole the rock possesses few of the more obvious features characteristic of that mineral. Microscopic examination shows for the most part a fibrous mineral which is distinguished by its high interference colors, parallel extinction and correspondence of the direction of least elasticity with the cleavage trace. These features all indicate the mineral anthophyllite. In addition there are found considerable amounts of serpentine, grains of magnetite and fine veins of calcite.

For the chemical examination a mass bounded by freshly-exposed surfaces only was employed. The finely-ground powder

was partly decomposed by hydrochloric acid after long digestion. The analysis reported in Table VI shows a remarkably high percentage of combined water, which can scarcely be accounted for unless the existence of a hydrated anthophyllite be admitted. The specific gravity was found to be 2.756.

ALBITE.

This mineral is found in the crystalline schists, especially those containing quartz and glaucophane. In one mass of these schists from locality B there is present a vein some six inches in width and visible for a distance of some twenty feet, which consists of crystals of the pure mineral. They are uniformly twinned according to the albite law, but are too opaque to admit of microscopic investigation. The analysis recorded in Table VI shows that the mineral possesses no unusual features but clearly indicates that the process of kaolinization has begun.

NOTE ON THE PROBABLE RELATIONSHIPS OF THE ABOVE MINERALS.

Though aside from the principal objects of the present paper, some observations on the occurrences and probable genetic relationships of the minerals here described are not out of place. The physiographic features of the principal locality represented (B) may be briefly described as a gentle hill slope extending from the top of the ridge which forms the western wall of Wildcat Cañon, to the alluvial plane surrounding the Bay of San Francisco. It is transversed by numerous small water courses, which are rapidly sculpturing the slope into a series of distinct hills. The principal rock formations represented are serpentine in its various forms and a series of crystalline schists, both of which formations outcrop at various points over the entire surface, but are more strikingly revealed in the form of projecting masses or ledges, sometimes extending to a height of twenty feet above the prevailing slope. Various stages in the alteration of pyroxenite, the ultimate result of which is serpentine, are to be found, but the latter often assumes the form of compact blue-black

masses which are probably derived from peridotite. Ledges of the serpentine weather out into most fantastic forms, composed of a porous, kaolin-like material, in which all evidences of the original structure have been lost. They are not infrequently traversed by veins of quartz, some of which is coarsely crystalline.

The crystalline schists also present many variations in structure and composition, the most striking features being a tendency for the segregation of the constituent minerals into fairly homogeneous pockets or veins. Practically pure masses of actinolite, glaucophane, chlorite, talc, albite, and quartz may be obtained from the same rock mass. Gradations between such occurrences and the strictly schistose portions, composed of finely crystalline minerals only, are to be found. Evidences of crumpling and distortion of the mass after crystallization has taken place are revealed by deformations (curvatures, twistings, partings, etc.) of the individua crystals and by the curvature of the plane of schistosity itself.

The true connection between the two formations is an obscure one. Contact between the two was observed in a single instance, and that of a rather indefinite character, the only feature worthy of note being the tremolite which has been already described. The chemical features seem to show that there is a general relationship between the two formations, since both groups of rocks represent magmas, comparatively rich in magnesia and lime and poor in iron and alumina. The rather unusual occurrence of soda in the pyroxenite also indicates a relationship with glaucophane- and albite-bearing schists, but there seems to be, as yet, no means of determining the exact nature of this relationship.

The occurrence of actinolite in the form of nodules many of which are rounded and polished, though said to be not uncommon in the Coast Ranges, is, on the whole, an unusual one, and suggests an inquiry as to the geological peculiarities to which this feature is due. Two possible theories (one chemical and the other dynamical) suggest themselves. According to the former theory, the nodules arose from peculiarities in the composition of the peridotites and pyroxenites which preceded the serpentine, whereby from certain centers of crystallization spherical aggregates were formed and segregated as definite structures in the subsequent disintegra-

tion of the rock. This theory would explain their rounded character, and is supported by the occasional occurrence of nodules with indications of such a center of crystallization, but other facts are not in harmony with this view. The evidence seems to point to the fact that the actinolite is all derived from the crystalline schist. In no instance were the nodules found in the serpentine, and there was a striking absence of actinolite-containing fragments below the serpentine areas. Also the characters of the actinolite from the schist and from the nodules are identical, the variations in the form and size of the crystals, their deformations (curvatures, etc.), are repeated in both, the chemical composition is essentially the same, and the associated minerals show the same range of variation. There is, however, insufficient evidence of the separation of the nodules as distinct structures in the original schist, though suggestions of this are furnished in the lenticular or pocket-like masses occasionally encountered.

A dynamical theory would require the action of forces capable of disintegrating the schistose rock, and of grinding or shearing forces capable of rounding and polishing the more or less angular fragments thus produced. Examination of all the actinolite-containing fragments of a given area shows that only a part of these have attained the perfect boulder form; they are often present as angular or only partly-rounded fragments, many of which show a suggestion of the schistose structure. Furthermore, those areas which show the greatest number of perfect actinolite boulders also show rounder masses of other minerals (glaucophane, etc.), though the former are decidedly more frequent. The latter facts may be due to differences in the resisting powers of the different minerals to the agencies concerned. The nature of the agency concerned in such a grinding and polishing process is somewhat difficult to indicate. Streams of water of high velocity could readily accomplish the desired result, and occasional boulders, which were found in the bottom of stream beds, possessed the rounded and polished character in a high degree, but, presumably, this agency is of too local a character to account for all the phenomena. Aside from this there is evidence of intense movement and shearing action of the rock mass in the crumpled character of

the schists, and it is evident that much of this transpired after the separation of the actinolite crystals. It would clearly require, however, a long succession of such movements to produce the phenomena here observed, and satisfactory evidences of this are not present, nor could it have been expected that they would have been retained.

University of California,
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THE BERKELEY HILLS

A DETAIL OF COAST RANGE GEOLOGY

BY

ANDREW C. LAWSON AND CHARLES PALACHE.

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Strawberry Cañon from University Campus. Sky-line Ridge on right, showing erosion-forms of Chico in foreground. The prominent peak, Sugarloaf, is composed of Monterey cherts and shales. Frowning Ridge Escarpment on the extreme left.

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INTRODUCTION.

The Berkeley Hills have rather vague limits. The term is a popular one applied with a certain affection to the range which overlooks the city of Berkeley and the Bay of San Francisco. Its culminating point rises, a little to the east of the University of California, to an altitude of nearly 2,000 feet above sea-level. From Berkeley the range extends southeastward, behind the city of Oakland, with a very even and continuous westward front, off towards Mount Hamilton, into which it merges. To the northwest it persists as a prominent feature of the landscape to the mouth of San Pablo Creek, beyond which it continues only in the form of rolling hills of comparatively low elevation. On the east this range is delimited by San Pablo and Moraga Valleys. It is thus but a simple ridge, though a dominant one, of the belt of the Coast Ranges, which is generally known as the Mount Hamilton Range, and which includes many separately-named ranges and groups of hills.

To what portion of this range the term Berkeley Hills applies is rather a matter of popular usage than of scientific determination. Whatever may be their extent, the heart of the Berkeley Hills is the field discussed in the present paper. The study is by no means exhaustive, and the area considered is practically limited to that represented on the accompanying map, except for occasional drafts on information obtained from adjoining portions of the Coast Ranges to supplement the observations here recorded.

The area embraced in the map is less than six square miles, and represents only about one-fifteenth of the cross section of the Coast

Ranges, yet in this limited section there are not less than 31 geological units, many of them complex within themselves, which have been found worthy of cartographic representation upon the scale adopted, viz., 1:12,000. The chief results of the study are a partial elucidation of the later Tertiary history of the region of the middle Coast Ranges. The subdivision of the older series of formations, such as the Franciscan, Shasta-Chico, and Monterey, has not been attempted on the map, although certain possibilities in this direction are indicated in the text. Other portions of the middle Coast Ranges, in the same geological province as that with which we have here to deal, are known to afford better opportunities for the study of these older Mesozoic and Tertiary formations, and all that could be done in the way of cartographic subdivision, even on the advantageous scale adopted, would have contributed little to our knowledge of their stratigraphic composition and internal relations.

In contrast to the broad mapping of these older series, the various formations of Pliocene age are rather minutely, though not exhaustively, subdivided; and in the relations of these minor subdivisions we have been able to decipher a new and most interesting chapter of Coast Range geology.

The work has engaged the attention of the senior author in a rather desultory way for several years past, while his collaborator contributed much to the geological mapping, and studied particularly the petrography of the volcanic rocks when he was a graduate student at the University of California. The senior author assumes responsibility for the general discussion, while the section dealing with the microscopic petrography of the volcanic rocks is the work of Dr. Palache.

The topographic basis of the geological map is the work of the late W. H. Otis, and is for the most part a very faithful representation of the relief, although there are portions of it which fail to express the surface features adequately to the scale upon which it is constructed.

The authors are under obligations to Professor J. C. Merriam for the determination of the various fossils referred to in the text, except where otherwise stated.

The area mapped has served for the past eleven years as a training-ground for successive classes of students in field geology. The great variety of formations and the complexity of structure which characterize the field, coupled with its close proximity to the University, and its accessibility at all seasons, have been of great advantage in the work of instruction in geology. In the examination of the ground by these classes not a few observations have been contributed by the students. It is anticipated that they will be the readers most interested in this essay. In writing it, the service which might be rendered to future classes in field geology has always been borne in mind. This fact will explain to geological readers at a distance the somewhat elementary treatment given to certain phases of the subject, the effort having been throughout the paper to make it not only a description and discussion of the field, as a general contribution to the geology of the Coast Ranges, but also to arrange the sequence of observations on the lines which have been found most profitable for the field class to follow in the study of the region.

GENERAL SECTION OF THE BERKELEY HILLS.

FRANCISCAN SERIES.

Sedimentary Rocks.—The first rocks that we meet with in approaching the Berkeley Hills from the gentle slope upon which the town of Berkeley is situated, are by no means easy to characterize in a few words. On the University Campus, in some of the older excavations, as at the Conservatory and North Hall, and along some of the road cuttings, there are exposures of a rather hard bluish-gray sandstone which weathers to a rusty yellow color. The same rock is exposed in the bed of Strawberry Creek just above the College Avenue entrance bridge. This sandstone is of a massive character and has a uniform, moderately fine, texture. Although traversed by numerous quite irregular divisional planes, it is practically impossible, as a rule, to detect in the exposures available any satisfactory evidence of bedding or stratification. This type of sandstone is common in the region about the Bay of San Fran-

cisco, and is, indeed, of extensive occurrence in the Coast Ranges generally.

In the older writings on Californian geology it was referred to as the San Francisco sandstone, from its prevalence at the city of San Francisco. In later years it has been recognized as a constituent member of a series of formations to which the name Franciscan has been given. Other formations are characteristically associated with this massive sandstone to make up the Franciscan series. Among the most interesting of these are certain rhythmically bedded, flinty rocks, or cherts, which are known to geologists as radiolarian cherts, from the occurrence in them of numerous fossil remains of the minute tests of radiolaria, or the casts of such tests. These radiolaria were marine animals which secreted a silicious skeleton or test of great beauty and complexity of structure, which sank on the death of the animal and became entombed in a silicious ooze then accumulating on the sea bottom. Their fossil remains may be readily seen by examining a smooth surface of almost any fragment of the chert with a pocket lens, and the observation is made much easier by wetting the surface. In thin section of the chert they appear on the stage of the microscope usually as discrete rounded areas of clear chalcedony, about .25 mm. in diameter, in a matrix of microcrystalline quartz, and quite commonly remnants of the original form of the test may be detected. The forms of these tests are very varied, and each particular species had its own peculiarity of skeletal architecture; and it is upon this basis that they are classified. Numerous genera and species are represented in the radiolarian cherts of the Franciscan series, but the distribution of these creatures in geological time is not yet sufficiently well known to enable us to determine the age of the rocks in which they occur, except in a very broad way. That is to say, although these fossils indicate that the rocks are of Mesozoic age, the subdivision of the Mesozoic, to which they belong, can not be indicated with certainty. The rhythmically thin bedding of these radiolarian cherts is one of their most interesting features, and the one which is most difficult to explain. The absence of detrital material in these cherts of course indicates that they were laid down on a sea bottom deep enough to be far

removed from ordinary terrigenous sedimentation, and yet their stratified upbuilding in thin layers of hard chert alternating regularly with partings of a peculiar shale, points clearly to a rhythmical oscillation of the conditions of accumulation, and the significance of the rhythm is as yet an unsolved problem.* These rocks may be observed on the lower slopes of the Berkeley Hills, north of Berkeley, and to still better advantage in the Piedmont district of Oakland, particularly on the ridge to the north of Oakland Park.

Another interesting formation of the Franciscan series is a compact light gray limestone, with which are generally intercalated thin lenses and sheets of dark chert. On a smooth surface of this limestone there usually may be seen small hyaline spots resembling somewhat the fossil radiolaria in the red cherts just described, but they are not so round. These are also fossils, but of an entirely different order from the radiolaria. They are the casts of chambered calcareous shells of various species of foraminifera, and the rock is therefore known as a foraminiferal limestone. This limestone is unfortunately not exposed along the base of the Berkeley Hills, and the nearest outcrops at which its acquaintance may be cultivated are on the San Francisco Peninsula and in Marin County, near Tomales Bay. There are, of course, associated with the sandstones of the Franciscan series also shales and conglomerates, and the former may be seen well exposed in some of the road cuttings in the hills back of Oakland. At the mouth of Strawberry Cañon in the creek bed the shales crop out for a few yards, but they have been intensely sheared and crumpled so that they have rather the character of crumpled phyllites than ordinary shales. They are, in respect of their deformation, in strong contrast with the little disturbed shales of the Knoxville series, which, resting upon them, are exposed a little above on the cutting of the cañon road.

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*For an account of the occurrence of radiolarian cherts in the Bay region, see Ransome on The Geology of Angel Island, Bull. Dept. Geol. Univ. Cal., Vol. 1, No. 7. Also Lawson, Sketch of the Geology of the San Francisco Peninsula, 15th Ann. Rpt., U. S. G. S.

Eruptive and Intrusive Rocks.—There are also certain basic eruptive rocks, which were laid down as lavas and tuffs at the time of the accumulation of the sandstones, and a great abundance of intrusive rocks, which invaded the series after its accumulation. These intrusive rocks are of two general kinds: (1) Diabases and basalts, very frequently showing a spheroidal structure, and sometimes variolitic on their margins. (2) Peridotites and pyroxenites, now almost completely serpentinized and not uncommonly associated with gabbros, which appear to have been differentiation products from the same general magma as that which yielded the peridotites. Both of these classes of intrusives are to be seen within the limits of our map in the bed of Strawberry Creek, between College Way and the mouth of the cañon, and a small area of serpentine occurs in Hamilton Gulch, as is indicated on the map. It is to be noted that, while the diabase and basalt intrusives are confined to the Franciscan rocks, there are occurrences of serpentine in various parts of the Coast Ranges which seem to indicate that certain of these peridotite intrusions took place at a date so late as to pierce also the overlying Knoxville series.

While the occurrences of serpentine and basaltic rocks within the limits of the map are too limited and too much decomposed for advantageous study, much more extensive and satisfactory exposures of these rocks may be seen to advantage both to the north and to the south of Berkeley, along the same general line of outcrop of the Franciscan. From a well ninety feet in depth sunk on the west side of Prospect Street, on the J. F. Sims property, there were brought up fragments of a dark porphyritic igneous rock, unlike any other rock known in the district. It was in a thoroughly sheared and decomposed condition, and is referred without question to the eruptives associated with the Franciscan. The deformed condition of the rock, taken in connection with the similarly-deformed phyllites, above referred to, at the mouth of Strawberry Cañon, indicate the presence of a shear zone of considerable movement along the immediate front of the Berkeley Hills. In the well in question this rock was mantled by not less than forty feet of alluvium and sandy deposits.

Metamorphic Schists.—Very commonly where these intrusions invade the Franciscan formations there is found in their immediate vicinity a more limited but very irregular and discontinuous zone of crystalline schists. These rocks can only be interpreted as the products of contact metamorphism resulting from the reaction of the heated emanations from the invading mass upon the encasing rocks. The best local illustrations of such occurrences are on Angel Island, which has been carefully studied by Ransome;* on the Tiburon Peninsula in Marin County, and on the flanks of the Berkeley Hills north of Berkeley. The most characteristic mineral of these metamorphic schists is the rare blue amphibole called glaucophane, and they are therefore commonly referred to as glaucophane schists. There is a small band of such glaucophane schist exposed for a few feet in width in the sandstones, in the portion of Strawberry Creek above referred to between College Avenue and the mouth of the cañon. The exposure is, however, unsatisfactory, and it is impossible to make out its relations to the eruptive rocks in the immediate vicinity.

We thus see that, although the exposures of the Franciscan on or near the campus are very limited in extent, we nevertheless have represented practically all of its characteristic rocks, with the exception only of the foraminiferal limestone.

SHASTA-CHICO SERIES.

Knoxville Shales.—As we begin the ascent of the hill on the south side of the mouth of Strawberry Cañon, we meet on the cuttings of the cañon road some beds of dark shale, some layers distinctly argillaceous, others more sandy. These beds slack readily under the atmosphere with a roughly concentric spherical fracture and pass into soil readily; so that they are not seen in natural exposures, and even in the road-cutting crumble away and are mantled by the hill-wash from above so rapidly that they are not now easily observable without some digging. These shales are characterized in places by an abundance of rusty-yellow limonite concretions, ranging in size from the dimensions of a nut

* Loc. cit.

to nodules several inches in diameter and having a very sharply-marked concentric structure. Owing to the obscurity of the exposures, the thickness of these shales can not be ascertained, but they form a well-marked horizon along the base of the hills, and appear wherever they are exposed to be the chief constituent of the basal formation of a thick series of rocks reposing upon the Franciscan rocks above described. The dip of these shales is easterly or into the hill at an angle in the road cutting above mentioned of about 30° to 40°. The probable course of the concealed edge of this shale formation between the mouth of Strawberry Cañon and Hamilton Gulch is marked by a landslide topography. In the shale on the road cutting there has been formed an ammonite belonging to the genus *hoplites*, and in other outcrops of the same formation both to the north and to the south of Berkeley forms of *aucella Piochii* have been found. Both of these forms occur characteristically in the Knoxville formation, which is the basal member of the Shasta-Chico series. On the basis of these fossils, and on account of the petrographic similarity of the whole with the Knoxville shale in other parts of California where fossils are more abundant, as well as the stratigraphic position of the shales, the formation of which they are a part is referred with little doubt to the Knoxville or lower member of the Shasta-Chico series.

Unconformable Relation to Franciscan.—On passing from the Franciscan rocks to the overlying strata, whether they be Knoxville shales or still higher beds, we can not fail to be impressed with the general contrast in the character of the respective formations. The Franciscan sandstones, for example, appear to be much harder and more firmly cemented than the sandstones of later age. Large quarries have been opened in the Franciscan sandstones in the low foot-hills between Berkeley and Oakland, from which a large part of the macadam has been obtained for paving the streets of these cities. The sandstones of the Shasta-Chico series are equally available for this purpose along the front of the range, but are unsuitable because of their greater softness. The lower rocks, moreover, have evidently been subjected to a greater degree of disturbance than have the overlying strata. They are frequently

slickensided and seamed with small veins; and in both these respects are in contrast to the Shasta-Chico beds. The Franciscan beds have very generally been invaded by the intrusions of a basaltic rock which never pierces the Knoxville. The Knoxville beds are never affected by metamorphism so as to develop the contact zones of glaucophane and other schists which are common features of the Franciscan.

These facts clearly indicate that the Franciscan rocks have passed through a history which has not been participated in by the overlying Shasta-Chico. The Knoxville shales lie indifferently upon the various formations of the Franciscan, and we are, therefore, forced to the conclusion that the latter must have been orogenically disturbed and worn down by erosion to afford the surface upon which the Knoxville beds were deposited. We are thus warranted in the belief, that we are here dealing with one of those epochs in geological history in which the record of geological time is marked, not by the accumulation of sediments, but by their erosion and removal. It is sometimes spoken of as a hiatus in the geological record, but it is only a gap in the record of sedimentation not in the record of geological events. Structurally it is referred to as an unconformity, and the Knoxville strata repose, therefore, unconformably upon the Franciscan.

Chico Sandstones.—As we continue the ascent of the hill, following Panoramic Way, we meet with sandstones with subordinate intercalations of shale all the way to the summit of Skyline Ridge. In the cuttings by the side of Panoramic Way we may see that these sandstones are in places distinctly bedded, but away from the road the outcrops usually show no evidence of stratification, and on the roadside where the stratification may be best observed it is also very apparent that the strata, locally at least, have suffered considerable disturbance. Dislocations and thrusts of limited extent traverse the beds in various directions, and the softer shale beds, between the harder and more resistant sandstone beds, have been intensely deformed and crumpled. Inasmuch as phenomena of this kind are not commonly observable in other parts of this set of rocks, we may conclude that the shattering of the rock is indicative of a local zone of disturbance. This shattering must not be con-

founded with the normal disintegration of the sandstone in the superficial zone of weathering. In the latter case the sandstone is broken up into angular pieces by the intersection of divisional planes along which no movement has taken place. The disintegrated zone extends down for several feet below the surface, and the angular fragments become rapidly smaller towards the surface, and eventually pass into the soil. In this disintegration of the surface zone of rock under the influence of alternate saturation and desiccation and of other meteoric agencies, we have an excellent illustration of the general process of the conversion of rock into sedentary soil.

These sandstones, with their subordinate beds of shale, occur in large stratigraphic volume on both sides of Strawberry Cañon. On the north side they are found extending to the top of Serene Hill and across Wolsey Cañon; and on the south side, as before stated, to the summit of Skyline Ridge. They also form the bed-rock over which run the waters of Strawberry Creek and Hamilton Gulch. They are also well exposed in Telegraph Cañon and abundantly along the range to the southeast, but to the northwest the formation thins out rapidly and we see little of it beyond North Berkeley. The general strike of the rocks is coincident with the trend of the range, and the general dip is easterly, or rather northeasterly, but at variable angles, and no section in the vicinity of Berkeley reveals the attitude of the rocks sufficiently well to afford data for a satisfactory estimate of the thickness of the series. It is probably, however, not less than 2,000 feet.

The only fossils which these sandstones have yielded in the vicinity of Berkeley are fragments of a large *inoceramus* and a small *pecten*. A few miles along the range to the southeast, however, at Shepherd's Cañon, a number of *echinoderms* and other fossils have been found which indicate the Chico age of the rocks, and the sandstones are of the same petrographical character as those of the established Chico in not distant parts of the Coast Ranges. They are, therefore, regarded as a part of the Chico formation. The highest part of the formation on Skyline Ridge is a thickness of perhaps fifty feet of a soft ocherous-yellow, friable

sandstone. It is mapped with the Chico doubtfully since it differs materially from the ordinary sandstone of that formation.

Conglomerate, Aporhyolite, and Serpentine.—The continuous section of Shasta-Chico sandstone and shales which is observed by ascending Skyline Ridge from a point near the mouth of Strawberry Cañon, by Panoramic Way, is not paralleled on the south side of Hamilton Gulch. If we ascend the ridge in the line of Dwight Way, the first rocks met with after leaving the alluvium are an exposure of a pebble conglomerate of very limited extent near the residence of Mrs. Gibbs. This conglomerate resembles a conglomerate which is traceable for many miles along the front of the range between the Knoxville and Chico. Immediately above this we meet with a soil which is of a rusty red color and is made up largely of small fragments of an oxidized volcanic rock. The true character of the rock would not be guessed at from an inspection of these chips, but on following it around into Hamilton Gulch, an excavation which has been made in the hillside affords an exposure, and outcrops of the fresh rock are to be found higher up on the slope. From those it is evident that the rock in its less decomposed condition is a compact, bluish-white, microcrystalline rock of a hard and silicious character. It frequently contains numerous minute crystals of pyrite, and it is the oxidation of these which gives the fragments and the soil derived from them their ocherous appearance. A microscopic study of this rock shows that it is made up essentially of quartz and feldspar, with very little of the ferro-magnesian silicates, and it is regarded as an altered form of an ancient flow of rhyolite lava. It is therefore designated an aporhyolite.

This aporhyolite occupies the precipitous hill at the head of Dwight Way to an altitude of more than 300 feet above the point where it is first met with. The steep slopes and red soil to which it gives rise are in marked contrast to the gentler slopes and gray soil yielded by the Shasta-Chico sandstones on the north of Hamilton Gulch. Followed into Hamilton Gulch, the aporhyolite extends only to the creek line, the lower limit of the formation keeping approximately on the same level. On the south side it extends up the creek for about 700 feet, abutting squarely upon the

sandstones which occupy the north side of the creek. This mass of aporhyolite is the northern end of a belt of such rock, which is traceable along the front of the range for many miles to the southeast, and its abrupt termination, with a thickness of over 300 feet, in the creek line of Hamilton Gulch, clearly indicates that it stops against a fault. The eastern limit of the mass is a nearly vertical plane, the trace of which is best seen in the cañon immediately to the south of the map. This limit is, therefore, also a fault. On the map the aporhyolite is represented as reposing directly upon the Franciscan. This is its relation in portions of its extension to the southeast, and the conglomerate, which apparently intervenes between the two formations, is omitted from the section at the head of Dwight Way. Considerable doubt exists as to the actual sequence in this section below the base of the aporhyolite, owing to the obscurity of the exposures, and the presence of the Franciscan as mapped is inferred from the relations observed in other sections. It seems probable that whatever Shasta-Chico may intervene between the aporhyolite and the Franciscan must be of very limited volume.

In the midst of the aporhyolite at its base in Hamilton Gulch is a small area of serpentine less than half an acre in extent. This serpentine extends only to the fault line, and is not seen on the north side of the Gulch. It represents a serpentinized peridotite, which must either be intrusive in the aporhyolite or be a portion of the surface upon which it was extruded. In the absence of any evidence of intrusion, the latter view has been adopted as consistent with the relations of the same rock to serpentine in the hills back of East Oakland, and this interpretation of the relation of the serpentine to the aporhyolite supports the view that the aporhyolite reposes directly, in part at least, upon the worn surface of the Franciscan. If this be so, then the two faults which bound the aporhyolite on the north and east have affected the upthrust of the latter against the Shasta-Chico sandstones. The extent of this upthrust on the east fault can not be less than 400 feet. This fault is traceable across the hills to Telegraph Cañon, and shows in various places evidence of intense disturbance along the plane of dislocation. The east and west fault crosses Skyline Ridge obliquely, and descending into Strawberry Cañon, abuts upon

another longitudinal fault, to be described later as the Cañon fault. The differential downthrow along the entire length of the fault is to the northward.

The conglomerate referred to in the preceding section as intervening between the Knoxville and the Chico, traces of which are found near the head of Dwight Way, is significant of an important change in the conditions of sedimentation at the close of the Knoxville. The fine shales are replaced by coarse pebbles, indicating a disturbance of the region from which the sediments were derived, whereby the streams had their grades accentuated and their powers of erosion and transportation greatly increased.

THE MONTEREY SERIES.

Unconformity.—The general trend of the crest line of Skyline Ridge is transverse to the strike of the formations, and, as the general dip of the latter is northeasterly, we meet with successively higher or later formations as we pass along the ridge towards the summit of the range. The next formations, therefore, which we should naturally expect to find in this section lying upon the Chico would be those of the Eocene. There are two main divisions of this series, viz., the lower or Martinez formation, and the upper or Tejon formation. But, although both of these are represented by thick accumulations of sandstone replete with fossils in the neighborhood of Martinez, not many miles distant, they are not found in our section, and the next rocks that we meet with in ascending order are those of the Monterey series (Miocene). We have here, therefore, a fine illustration of a geological gap or hiatus, there being a long interval of time between the Chico and the Monterey, for which we have nothing to show in the shape of sedimentary deposits. There are of course two possible explanations of such a hiatus. Either the region now occupied by the Berkeley Hills was dry land during Martinez and Tejon time, so that no marine sediments were ever laid down upon the Chico, or the sea of these periods extended over the region as elsewhere in the Middle Coast Ranges, and the Martinez and Tejon formations, which were then deposited, were removed by erosion in consequence of an uplift which intervened prior to the Monterey submergence. Without

stopping at present to critically examine these two possibilities to determine which is the correct explanation, it may be remarked that, whichever explanation we adopt, there is implied the superposition of the Monterey formations upon a surface of Chico rocks which had been subjected to the degrading influence of subaerial erosion, so that we have here all the conditions of an unconformity. The recognition of this unconformity is one of the important lessons to be learned in the study of the section.

Cherts and Shales.—Following the crest of Skyline Ridge, the rocks of the Monterey series are first met with at a point about 1,700 feet southwest of the summit of Sugar Loaf. The first indication that we meet with of a passage from one formation to another is the change in the character of the soil; for at the actual contact on the Ridge crest there is no prominent outcrop of rocks of either formation. Instead of the gray or yellowish sandy soil which mantles the Chico rocks, we meet with a light soil free from sand, but abounding in angular fragments of rather hard whitish shale or of a much harder flinty rock, to which the term chert is applied. A few minutes' search on the steeper portions of the slope or on the summit of the hill which rises abruptly as soon as we meet with these fragments, will reveal ledges or outcropping edges of the beds of this formation. These all show a thinly and evenly-stratified character, with very commonly an alternation of chocolate-colored shale with a flinty dark chert. The white color of the angular fragments found in the soil is due to a bleaching of the rock under the influence of weather and vegetation. Rocks of this character crop out abundantly along Skyline Ridge to a point about 625 feet beyond the summit of Sugar Loaf, and it is evident that we have to deal with a voluminous formation of a remarkable and fairly uniform petrographic character. When, however, we examine the various outcrops critically we find that the cherts vary somewhat in detail. Some beds are quite homogeneous, while others, still thoroughly flinty, show a fine laminated structure, the laminæ being parallel to the bedding planes. The color of the chert is in some cases coal black, as on crest line at the west base of Sugar Loaf, and in other occurrences it has a purplish cast, although its general appearance, where not bleached, is a dark

Cherts and Shales of Monterey formation, n quarry near head of Telegraph Cañon, showing characteristic rhythmical bedding.

brownish or yellowish gray. The relative proportion of chert and shale in alternation of these two rocks is also rather variable, although in general the chert beds preponderate and the shale is but a thin parting. The most characteristic outcrops exhibit very regular beds of chert, ranging from one inch to six inches in thickness, with shale partings from one-eighth to one-half inch thick. In this remarkable regularity and rhythm of stratification the formation closely resembles the radiolarian cherts of the Franciscan series. Occasionally single chert beds are a foot or even two feet thick, but this is unusual; the shale appears in certain cases to diminish to a mere film or to be altogether lacking in the parting between the chert beds. The dark brownish or yellowish-gray color of the cherts and the chocolate color of the shales appear to be due to the presence of bituminous matter, since on ignition the color may be discharged with the emission of a distinct bituminous odor. Some of the beds are composed of amorphous silica of a chalky consistency, and in these cases the characteristic lamination is not well developed. The presence of the bituminous matter as a characteristic feature of a large part of the Monterey series, wherever found in the Coast Ranges, whether shaly or chalky or cherty, has caused them to be referred to frequently as the "bituminous shale* formation."

Fossils are scarce in this formation, the only forms known being *Tellina congesta*, *Pecten peckhami*, fish scales and casts and moulds of foraminifera, all occurring in the shales.

Sandstones and Limestones.—A careful examination of the section along the ridge crest will reveal, besides the minor variations mentioned above, that the cherts and shales are not the only constituents of this formation. On the knoll to the west of Sugar Loaf there is found capping the ridge a bed of sandstone of a dark bluish-gray color, resting upon the cherts and shales. This sandstone contains considerable carbonate of lime, and in it are formed numerous casts of molluscs, which, though too imperfect for complete identification, are probably of Monterey age. A collection of these Molluscan remains was submitted to Dr. W. H. Dall, who kindly reported that, while the fossils were too poorly preserved for

*Also "bituminous *slate* formation;" but this is a misnomer.

specific identification, he thought he could recognize species of the genera: *Tapes*, *Cytherea*, *Anthomya*, *Arca*, *Macoma*, *Lucina*, *Tellina*, and *Neverita*, and that he considered the determination inconclusive as to the age of the beds. This is the only known occurrence of this fossiliferous sandstone, and it is doubtless a mere remnant of a formation which once overlaid the cherts and shales, and which, therefore, can not be regarded as a constituent part of this formation of the Monterey series.

But, leaving this aside, there are numerous beds of a peculiar, whitish, fine-grained sandstone, and of a gray, ocherous-weathering limestone which are distinctly interbedded with the cherts and shales, and which must from their persistent occurrence be regarded as integral portions of the formation.

The sandstones are usually not more than two or three feet in thickness, and are chiefly noteworthy as fragmental deposits intercalated in a formation of chiefly non-clastic origin. They are remarkably uniform in respect to their fine texture, the constituent particles being not easily distinguished without the aid of a lens, their whitish color, their mottled aspect, their highly silicious character, and their limited thickness. Thus characterized they are readily distinguished from almost any other sandstone of common occurrence in the Coast Ranges. Their unique character extends to their microscopic structure. When examined, in thin section on the stage of the microscope, they are seen to be made up of an aggregate of sharply-angular fragments of quartz of fairly uniform size in a cement of an earthy isotropic substance similar to that which makes up the bulk of certain chalky-white varieties of "bituminous shale" from this and other portions of the Coast Ranges. They thus differ in an essential particular from ordinary silicious sandstones, and, indeed, seem to constitute a new and peculiar type of fragmental silicious rocks.

The ocherous-weathering limestones, which, equally with these peculiar sandstones, characterize the formation, deserve also a special note. They have a dense, compact texture, and show no trace of fragmental or of organic origin, and thus differ from most ordinary limestones. No fossils have ever been found in them. Chemically as shown by their weathering they contain carbonate of

iron, and, like most of the beds found in the Monterey series throughout the Coast Ranges, are also magnesian. They are usually less persistent along their strike than the sandstone beds above described, and are to be regarded rather as discrete lenses than continuous beds. The limestones and sandstones together are estimated to make up less than five per cent of the entire thickness of the section.

The rocks of the Monterey series as represented in this section must, from the foregoing description, be regarded as a peculiar formation which has been laid down under conditions which differed radically from those which have obtained in ordinary basins of sedimentary accumulation. In the shales which interleave the chert beds have been found certain fossil molluscs, such as *Pecten peckhami*, which are characteristic of the Monterey series and which establish the marine origin of the formation as a whole. The cherts ordinarily show no fossil remains, but in thin sections of a few specimens microscopic forms of minute organisms have been detected imbedded in the chert matrix, and these, of course, suggest that the silica of the cherts was in part at least derived from organic sources, but the general problem of the origin of the formation, which is presented by its remarkable composition, the mysterious rhythm of its stratification, and its intercalation of peculiar sandstones and limestones—this genetic problem is one whose discussion must for the present be deferred.

Monterey Only Partially Represented.—It should be observed before leaving this part of our subject that this formation, as exposed in Skyline Ridge, does not represent the entire Monterey series. The series in Contra Costa County, only a few miles to the eastward, is made up of an alternation of four fossiliferous sandstone formations and three formations of "bituminous shale," aggregating in all several thousand feet in thickness. Considerations which need not here be stated lead to the conclusion that the formation with which we have now to deal is the lowest of the three "bituminous shale" formations, or the second of the sevenfold series.

Having now become somewhat familiar with the petrographic character of the formation, we may turn our attention to its struc-

tural features, its volume, its distribution, and its relation to overlying formations.

Structural Features.—For the first thousand feet of the exposure of the formation along Skyline Ridge from the point where it is first encountered, the dip of the beds may be observed at numerous outcrops, both on the ridge top and more particularly on the steep upper part of the south slope. In no case are the beds found in their original horizontal attitude. They are tilted at various angles and in variable directions, and a careful plotting of the observable dips will show that the beds are acutely buckled and broken. In spite of this irregularity, however, two facts of importance result from these observations, viz.: (1) That the prevailing direction of the dip is easterly, and that the formation as a whole dips in this direction, notwithstanding local vagaries. (2) That the angle of dip is prevailingly of low value, *i. e.*, that the dip is much nearer to horizontal than it is to the vertical. As soon as we reach the flanks of Sugar Loaf, however, this lowly inclined attitude of the beds and of the formation as a whole abruptly changes. From this point on to the upper limit of the formation the attitude of the beds is continually vertical. We thus see that the minor portion of the formation is abutting obliquely upon the major portion, which makes up the prominent hill called Sugar Loaf. This relation affords us excellent evidence that the formation has been dislocated and that the two portions have been differentially shifted. We thus have presented to us the phenomena of faulting. A minimum value of the amount of dislocation is evidently measured by the thickness of the lowly inclined strata which abut upon the vertical beds. This is practically the measure of the height of the ridge above the road in Telegraph Cañon, or about 500 feet; for we find, on following the lower limit of the lowly inclined part of the formation down the south slope of the ridge, that this contact-plane also abuts upon the vertical beds just above the road. The actual amount of the dislocation may be much more than this minimum value. A fault with such an important throw could not terminate or die out within the narrow limits of the width of Skyline Ridge, and we should, therefore, expect to find evidence of its extension

in the country to the south and to the north of the ridge. This expectation, as we shall see later, is amply realized.

By connecting the point where we first encounter the fault on the summit of the ridge with the point where it intersects the Telegraph Cañon road, we see that the plane of the fault hades at a small angle to the west. On the assumption that we have to deal with a normal fault, this would indicate that the downthrow of the fault was to the west. This we shall find to be the fact, but as there are considerations which, taken alone, might lead us to think that we had to deal, not with a normal or gravity fault, but with a thrust making the upthrow on the west side, it will be better to defer the discussion of the real nature of the fault till we have become more familiar with the way in which it affects the country to the north and south of Skyline Ridge. It may be simply pointed out that the conditions which we have recognized on Skyline Ridge are in a measure duplicated on the south side of Telegraph Cañon. The fault will be referred to as the Cañon fault.

Thickness.—As to the thickness of the formation, since the strata from the fault plane to the upper limit of the formation are practically vertical, and since the section along the ridge is nearly normal to their strike, we have in this horizontal distance a measure of the volume of rocks exposed. This is about 1,000 feet. The value thus obtained, however, is only a minimum value for the thickness of the formation, for two reasons: First, because we measure not from the base of the formation but from a fault plane along which a part may have been sheared off in the process of dislocation; and, secondly, as will appear more clearly later, we measure not to the original upper surface of the formation but merely to a surface which has been established by erosion and upon which the next higher formation of rocks rests. A similar estimate for the thickness of these rocks is obtained by a measurement along the Telegraph Cañon road where the exposures in the road cuttings are much more satisfactory and practically continuous.

Geomorphic Features.—This belt of cherts and shales forms a prominent feature not only in the geology but also in the geomorphy of the Berkeley Hills, and is traceable along the strike of the rocks for many miles to the south. In this direction it forms

a sharp ridge or series of knobs of the Sugar Loaf type. Inasmuch as the forms of the hills are due entirely to erosion, it is apparent that the geomorphic prominence of this formation is due to the contrast in the degree to which it has yielded to the attack of erosive forces, as compared with the formations on either side of it. We have seen that the sandstones of the Shasta-Chico series yield hill forms which have in general smoothly-flowing contours and rounded profiles. Along the line of the Monterey formation the declivities are steeper and the profiles are more sharply convex. The formation to the east of the Monterey formation is softer and yields even more rapidly to erosion than the sandstones to the west of it, and in consequence the surface is lower and the slopes gentler. It is, therefore, due to differential erosion, or degradation, of the land mass of which the Monterey formation forms a part, that its relief is expressed so boldly. Were it composed homogeneously of chert, Sugar Loaf would be much more rugged and precipitous than it is. Its degradation is greatly facilitated by the soft shale layers, and the disintegration of the chert is wholly mechanical. It breaks up into sharply angular, cuboidal fragments or into flat chips which gradually move down the slopes or accumulate on the ridge tops. The formation in general yields but a very thin and poor soil.

The geomorphic features which thus characterize the formation in its extension southeastward are even more striking in its northwestward prolongation. The reason for this is that to the north of Skyline Ridge the Cañon fault, which has been referred to above, lets down against the westerly side of the formation a much softer set of rocks than the Shasta-Chico sandstones, and out of these soft rocks the central portion of the amphitheater-like depression of Strawberry Cañon has been eroded; so that the rocks of the Monterey formation present a very precipitous wall to the center of the amphitheater. This steep wall has been notched transversely by the several tributaries of Strawberry Creek, and we thus have a sharp ridge chopped up into a series of prominent knobs, of which Monument Hill is the largest and most typical.

The extension of the formation to the northwest is, however, quite limited, for the Cañon fault, which on Skyline Ridge dis-

locates the formation in a line parallel to the strike, curves to the eastward within a mile, and, crossing the strata obliquely, cuts off the formation completely, so that in this direction we have no trace of it beyond the periphery of Strawberry Cañon amphitheater.

ORINDAN FORMATION.

Stratigraphic Composition.—Continuing now our section along Skyline Ridge, we find a thick formation of pebble-conglomerates, feebly coherent sandstones, and purplish-red and greenish shale, which will be referred to as the Orindan formation. This formation has an extensive distribution in Contra Costa County in the region adjoining the Berkeley Hills on the east, and we must draw upon this region for information which will enable us to fully characterize the formation. In the part of the formation exposed along San Pablo Creek, beyond the limits of the accompanying map, and elsewhere in Contra Costa County, other beds than those just mentioned enter into its composition. These are thin beds of volcanic tuff generally decomposed and of a dark brownish color, beds of blue and slate-colored clay containing fresh-water ostracods, sandstones containing fresh-water ostracods, limestones containing fresh-water ostracods and molluscs, and occasional patches of lava of quite limited extent, intercalated(?) with the sedimentary beds. No marine organisms have been found in any part of the formation. These facts are here cited for the purpose of affording a more just conception of the formation as a whole than can be obtained from the section on the west flank of the Berkeley Hills, and of demonstrating its non-marine origin.

Unconformity at Base.—The contact of the base of the Orindan formation upon the underlying Monterey formation is clearly an unconformity. This is generally the case where fresh-water beds repose upon marine formations, but it is not a necessary inference that there must be an unconformity in all such cases, since it has doubtless not infrequently happened that arms of the sea have been converted into fresh-water basins without interruption of the process of sedimentation. The unconformity is established by direct evidence of the discordance of the two sets of strata, and

by the fact, drawn from a more general study of the region beyond the Berkeley Hills, that other formations, such as the upper part of the Monterey series and the San Pablo formation, which normally occupy this interval, are here lacking.

The basal beds of the Orindan formation are pebble-conglomerates, and their actual contact against the Monterey formation is well exposed on the lower two-thirds of the south slope of Skyline Ridge. The conglomerate bed is well cemented and affords a prominent outcrop showing a vertical dip, and the attitude of the plane of contact is clearly vertical. The bedding of the cherts is, however, not satisfactorily exposed. On the south side of Monument Hill the contact is again perfectly observable and here the bedding planes of the chert are better exposed than those of the conglomerate, and are seen to abut obliquely upon the contact plane, so that it is quite apparent that the conglomerates rest upon the basset edges of the chert beds. On the side of the ravine beyond Monument Hill a quarry has been opened in the chert formation for the purposes of obtaining road metal. The opening is close to the contact, which is again about vertical, and in the quarry face it is apparent that the chert and shale beds are intensely deformed, being, in fact, contorted and sheared in an intricate way, while there is no evidence that the conglomerates are so affected. They appear to lie across the abraded edges of the contorted cherts.

In the next transverse ravine the contact plane between the two formations presents an abrupt jog, which can only be interpreted as the heave of a fault which lies in the line of the creek. The extent of the heave is about 200 feet. Beyond this fault, to the northwestward, the plane of contact between the two formations gradually changes from a vertical attitude to a southwesterly dip, so that the beds of the Monterey formation appear to lie upon the Orindan formation, thus reversing the natural relations of superposition. This inverted dip both of the chert strata and of the contact plane is quite apparent on the last transverse ridge over which the contact is traceable, the angle of dip being variable but having an average value of about 70°. A little beyond this the entire Orindan formation is cut off by the Cañon fault just as the Monterey is.

To the southeast of Skyline Ridge the Orindan formation is traceable for many miles paralleling the Monterey formation on the northeast. On the ridge on the south side of Telegraph Cañon, over which is the summit pass of the Telegraph Cañon wagon road, the contact of the two formations is sharply defined; and here again the normal superposition of the Orindan conglomerates upon the cherts and shales is reversed, the latter lying upon the former with the beds dipping at an angle of about 60° S. W.

Owing to the softness of the rocks composing the Orindan formation, they yield a heavy soil and exposures are not abundant except along road cuttings and occasional steep slopes, so that the proportion in which the conglomerates, sandstones, and shales enter into its composition can not be definitely stated; but, judging from the great abundance of pebbles in the soil, the conglomerate greatly proponderates.

Thickness.—In attempting an estimate of the thickness of the formation, it must be again borne in mind that any result arrived at will be a minimum value for the formation as a whole. The observed volume of the Orindan beds within the limits of the area mapped may be placed at 800 to 1,000 feet. But it seems probable that the rocks here exposed represent the shallower margin of the basin in which these deposits accumulated; and it further seems not improbable that the upper limit of the formation represents a surface of erosion evolved after the basin of accumulation had been filled to the brim or had been drained.

Intrusives.—Some small basaltic dykes cut the Orindan formation as seen in the cuttings of the Telegraph Cañon road. The largest is a dyke, not more than 10 feet wide, with a slight northerly hade, which cuts the conglomerates a little to the south of the summit of the road. It is traceable for about a quarter of a mile directly across the strike of the beds which it cuts. The dyke rock is rather decomposed and affords a good illustration of spheroidal weathering. Two other dykes cut the sandstone of the Orindan formation in Telegraph Cañon near the chert quarry, but, being only from two to four inches wide and much decomposed, they are only observable when the rains have washed the face of the cutting clean.

Two small patches of fresh doleritic basalt occur low down in the Orindan formation on two of the transverse ridges above Such's ranch. It is not clear whether they are lavas in the Orindan formation or small intrusions of later date, or lava remnants of a later epoch which flowed out over the eroded surface of the formation. They seem to mantle the contact between the Orindan and the Monterey, and so the last interpretation has been placed upon their occurrence in coloring the map.

VOLCANICS ABOVE ORINDAN.

Continuing now our section, in the same general direction, we leave Skyline Ridge and climb the steep western slope of Frowning Ridge. This is one of the two dominant ridges of the Berkeley Hills, from which Skyline Ridge extends westerly as a transverse spur, forming the divide between Strawberry and Telegraph Cañons. Here we find resting upon the Orindan formation a great volume of stratified rocks which are preponderatingly volcanic. The accumulation comprises varieties of andesitic and basaltic lavas and volcanic tuffs both acid and basic, together with a subordinate proportion of gravels which are chiefly associated with the tuff beds. These volcanic rocks have proved much more resistant to the disintegrating action of erosive forces than any of the formations which we have as yet met with in our section. This fact finds its expression in the steep scarp-like acclivity of Frowning Ridge. Along the face of this escarpment, notched by various high-grade ravines, the constituent rock sheets of the accumulation crop out boldly. Many of these sheets may be traced in unbroken continuity throughout the length of the escarpment, as beds of varying thickness, between which are found lens-like masses of less extent. The harder rocks sometimes present almost vertical bluffs 20 to 40 feet in height; and in general the surface is unencumbered with talus and but little obscured by soil. An examination of numerous sections of the escarpment shows that, while the sequence of the rocks and the thickness of the individual sheets vary much in different places, the total volume of the volcanic material is remarkably uniform, the aggregate thickness being from about 800 to 1,000 feet. The strata thus outcropping

Frowning Ridge. Grizzly Peak on left. Showing volcanics of Berkeleyan with Orindan formation at their base.

on the face of the escarpment dip into Frowning Ridge, or northeasterly, at angles which vary from a little less than 30° to over 60°. Abundant evidence of the extrusive nature of the rocks lies before the observer. The parallelism of the rock-sheets over wide areas; the presence of pyroclastic material at different horizons; the zones of red laterite between successive sheets; the intercalation of detrital material, such as well-worn pebble beds, between the massive rocks; the glassy character of some of the sheets; the occurrence of vesicular and amygdaloidal structures and of flow structures well developed macroscopically and microscopically—all of these characters point to only one conclusion, viz., that the rock sheets were poured out as surface lavas. At several points the actual contact of the lavas with the associated sedimentary rocks may be observed, but in no instance can any alteration of the latter be detected, if we except certain inclusions of limestone in the lava which have become crystalline and in which silicates have been developed. The lavas may occasionally be observed to hold inclusions of pebbles, which may reasonably be regarded as incorporated portions of the surface over which it flowed.

Berkeleyan Series, Upper and Lower.—From the fact that several of the lava sheets have lateritic surfaces, which indicates a long exposure to weathering, and from the further fact that waterworn gravel is to some extent intercalated with the lavas, it is apparent that there were intervals between the successive flows. During these intervals not only would the surface of the lava be subject to decay under the processes of weathering, but the effects of erosion would be manifest in proportion to the duration of the interval; and if the region had been affected by deformation, such disturbance would modify the surface over which the next succeeding extravasation of lava flowed.

In respect to these two considerations, amount of deformation of the region and of erosion to which it was subjected, one of these intervals appears to be of much greater importance than the others; it is, therefore, regarded as one of those important epochs of geological history in which time and work are expressed in other terms than those of accumulation. The entire series of rocks, volcanic

and sedimentary, from the base of the Orindan formation to the crest of Frowning Ridge, is here named the Berkeleyan series, and the interval in question is regarded as a break in its accumulation, dividing it into Upper and Lower Berkeleyan. As we proceed with the examination of the ascending sequence on the escarpment of Frowning Ridge, this break will be pointed out at the proper place.

Amygdaloidal Andesite.—The basal member of the volcanic accumulation reposing upon the Orindan conglomerates is an andesite, which is perhaps the most persistent, and, at the same time, most uniform individual sheet of rock we have to deal with in our entire field. This uniformity in character has proved of the greatest value in establishing a stratigraphic datum plane across the Berkeley Hills. The breadth of the sheet indicates that the surface over which the lava flowed was a plain, probably a gravelly flood plane of the river which replaced the Orindan Lake after lacustrine sedimentation had ceased The lateral extent of this andesite sheet is in contrast to that of other lavas which succeed it; the latter seem to have been confined to narrower channels.

The thickness of this basal andesite varies over its entire extent from about 50 to 200 feet, with an average thickness of probably 100 feet.

The andesite is typically a grayish-black rock with a compact microcrystalline texture and even fracture, generally containing silicious amygdules of various forms and sizes scattered irregularly through its mass.

The fracture surfaces generally present a somewhat mottled appearance, owing to the presence of anastomosing streaks and spots of a yellowish or purplish color which transverse it. It does not anywhere present a porphyritic facies. Although amygdaloidal, the general aspect of the rock is not vesicular, the amygdules not being ordinarily so abundant as to be a conspicuous feature. Locally, however, highly vesicular varieties are found, and the amygdaloidal habit is characteristic of the sheet as a whole. It is for this reason designated on the accompanying map as the "amygdaloidal andesite," the amygdules and the mottled appearance serving to distinguish it from other andesites in this field.

The weathered surfaces of the andesite are dull gray in color, rough and pitted, the amygdules, when present, standing out in strong relief. The surface of the rock or the light residual soil which it yields are frequently strewn with amygdules which have weathered out of the matrix.

Mineralogical variations of much interest occur in the composition of these amygdules, but these will be discussed later, in the section of the paper that deals with the detailed petrography of the volcanic rocks, where a description of the microscopic character of this andesite is given.

The amygdaloidal andesite thus macroscopically characterized extends along the entire base of the Frowning Ridge escarpment, northwestward to the vicinity of Little Grizzly Peak, where it is cut off by the Cañon fault, and southeastward far beyond the Fish ranch cañon. The upper surface of the sheet is much decomposed and in places converted into a brick-red laterite, indicating an exposure to the atmosphere of considerable duration.

Tuffs and Basalt.—Resting upon this surface lies the second member of the volcanic sequence, a formation partly volcanic and partly detrital in origin. With the exception of a thin sheet of basalt of quite limited extent, the volcanic constituent is wholly pyroclastic and shows abundant evidence of having been sorted and stratified, but whether by air currents at its first deposition or subsequently by currents of water, is debatable. The presence of layers of gravel intercalated with the tuffs and in part mixed with them supports the latter hypothesis, although the water that transported and assorted the gravel was more probably fluvial than lacustrine. In its outcrop on the Frowning Ridge escarpment these beds vary in thickness from about 50 feet to over 200 feet.

On our line of section and northward to the line of the Cañon fault the formation has a threefold character. The basal 50 or 60 feet is a basic tuff, in the sense that it contains no quartz, partly fine-grained and partly coarse. It has in it fragments of andesitic lavas and a considerable proportion of water-worn gravel, partly volcanic and partly of the nature of ordinary polygenous stream pebbles, generally of small size. These rock fragments and pebbles, together with crystals and crystal fragments of feldspar and

augite, are imbedded in a very fine-grained paste, which is partly finer ash and partly a brick mudstone referable to the wash of the laterite of the underlying andesite. Part of the material mapped with this deposit may, indeed, be the sedentary laterite of the andesite, for it is difficult to draw the line between the two things. Some small patches of vesicular lava occur in it, representing unimportant flows.

Above this basic tuff and gravel layer, occurs a thin sheet of dark, coarse, doleritic basalt, which is not indicated by a separate convention on the map. It nowhere exceeds 20 feet in thickness.

Rhyolite Tuff.—Lying on this is the third member of the formation, the most interesting, most voluminous, and most persistent of the three. It is a thick bed of stratified rhyolite tuff. It appears as a fine to medium grained rock, of compact to porus texture, and a color varying from dirty white to tawny yellow. Its aspect is distinctly that of a clastic rock. Grains of quartz and fragmentary crystals of feldspar abound, and fragments of a fine-grained light-colored rock may frequently be seen, while darker fragments and pieces of a red or green color may also be occasionally detected. The stratification, while not always apparent in hand specimens, is generally readily observable in the field. Other outcrops than those occurring on the Frowning Ridge escarpment show a remarkably even bedding or lamination such as is usually only found in material sorted by water currents. It generally forms a hard, well-cemented rock weathering in rough forms.

The chief interest attaching to this rhyolite tuff is its striking petrographical contrast to the more basic lavas of the section, it being assumed that all the volcanic rocks emanated from practically the same volcanic center. The sequence of the rocks in the section from this point of view becomes of more than local importance, since it bears upon the problem of the differentiation of volcanic magmas, and contributes data to the question as to whether there is or not any definite sequence in the extrusion of lavas which may be regarded as a general law.

To the south of our line of section both the basic tuff and the doleritic basalt wedge out rapidly, although the lateritic facies of the former continues, and the rhyolite tuff alone persists. Even this

is found in greatly diminished volume, not exceeding 20 or 25 feet in thickness. The diminution of the volume of this tuff to the southward, along this line of outcrop, is regarded as additional evidence of its having been laid down in water, since, had it been deposited under the influence of air currents only, it would not have varied so rapidly in such a short distance.

Basalt Flows.—Above this threefold accumulation of basic tuff, doleritic basalt, and rhyolite tuff, is a belt of basalts. These have an aggregate thickness of from 150 to 180 feet, but neither the thickness of the individual flows nor their number can be satisfactorily determined. The rocks are uniformly fine-grained in texture and black in color. A more detailed account of their petrographic characters will be given later.

These basalts present a prominent outcrop along the entire front of the Frowning Ridge escarpment. To the northwest they terminate abruptly against the Cañon fault, like the older formations which underlie them. To the southeast the belt extends for many miles. The dip of the formation is uniformly into Frowning Ridge, or to the northeast at angles which do not vary far from 30°.

Grizzly Peak Andesite.—Continuing the ascent of the Frowning Ridge escarpment above these basalts, we next encounter a thick accumulation of lava flows which for the most part are of a different petrographic type from the underlying basalts. Laboratory investigation has shown that they should be classed with the andesites. These flows, though rather varied in character, are grouped together and are represented on the map by a single color, under the designation of the Grizzly Peak andesite, and it is understood that this color also covers certain subordinate flows of basalt and intercalations of tuff which are not considered of sufficient importance to indicate by a separate convention. The color on the map, thus designated, represents an assemblage of volcanic formations having in their aggregate a certain individuality, rather than a single flow or a set of flows of exactly the same kind of lava.

Of the andesite there are two rather distinct facies, represented by different flows, which may be readily distinguished even in the field. Of these the lower is a medium-textured holocrystalline rock, showing frequently a pronounced laminated structure, and

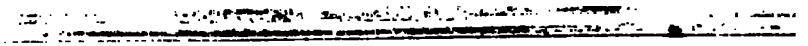
will be referred to as the holocrystalline variety of the Grizzly Peak andesite; the upper portion of the accumulation is, in contrast to this, a dense or compact rock, frequently glassy, with a prevailing porphyritic habit, and may be referred to as the prophyritic variety.

The holocrystalline variety of the Grizzly Peak andesite crops out prominently in a series of knobs on the buttresses which rib the Frowning Ridge escarpment from the Cañon fault to the head of Telegraph Cañon. These outcrops are generally characterized by a very distinct lamination, simulating the bedding of a sedimentary formation, but in reality a kind of jointage. The laminæ are from a quarter of an inch to three or more inches in thickness, sometimes forming lenses of limited extent, but more commonly preserving their continuity for considerable distances. They are generally parallel to the dip of the lava sheet, although, in places, they are undulating or sharply curved. An excellent illustration of this structural feature may be seen in the conical knob jutting out from the buttress just south of Grizzly Peak.

The rock exhibits considerable minor variety of texture and a tendency in places to merge by gradations into a facies resembling that particularly designated the porphyritic variety. Typical specimens, however, present the appearance of a massive rock, dark gray to reddish brown in color, with a rough or uneven fracture, and distinct, rather coarse porphyritic structure. Occasionally amygdules of quartz or natrolite are seen, and on weathered surfaces, which are generally smooth and of a dull gray color, a slightly vesicular or miaralitic structure is apparent. The phenocrysts comprise glassy feldspars and black pyroxenes, and, under a pocket lens, the ground mass is seen to be distinctly crystalline.

Certain beds of coarse breccia which are found intercalated between the flows of this lava are regarded partly as flow or klinker breccias, representing the original surface of a lava flow, and partly as formed of the cinders, ashes, and bombs which accumulated on the surface of the lava. These breccias chiefly consist of angular fragments and occasional rounded, bomb-like masses of andesite cemented with a fine ash-like material. The fragments are sometimes highly vesicular and are frequently thoroughly oxidized, so that they vary in color from gray and rusty brown to bright red,

Grizzly Peak Andesite, holocrystalline laminated facies. Exposure on South Slope of Grizzly Peak.



thus giving the rock a parti-colored aspect, and accentuating its heterogeneous character.

The porphyritic variety is typically developed in the upper portion of the Grizzly Peak andesite belt, forming the latest flows of this accumulation. It occurs in several sheets, the aggregate thickness of which ranges from 175 to nearly 300 feet. The outcropping edges of these sheets appear on Grizzly Peak and in the line of bold cliffs which form the summit of the Frowning Ridge escarpment. Typical specimens of the fresh rock show it to be deep black in color, massive and compact, containing numerous yellowish phenocrysts of glassy feldspar and rarer olivines embedded in a semi-vitreous base. In some specimens the base is less intensely black in color and of less compact appearance, but the porphyritic character is always strongly marked. It weathers variably; in some cases a mere film or crust of gray or reddish decomposition products is formed, beneath which the rock preserves its original character intact; more frequently it is extensively altered, the ground-mass changing to a dull red or brick red earthy material, and the feldspar becoming milk white and earthy. In some of the flows, as on the west face of Grizzly Peak, the vitreous character of the base of the rock is more pronounced than is usually the case, but such variations, due to proportion of glass present, can only be made out satisfactorily by microscopic examination. This more glassy facies is characterized also by an exceptional amount of brecciation, and, when this is the case, by more extensive decomposition. The angular or slightly rounded fragments into which the mass of the rock has been shattered have changed in color to various shades of gray and white, and are cemented by a fine-grained gray paste. The fragments still exhibit their original porphyritic structure, but as a whole the rock has entirely lost the igneous aspect of a fresh lava, and looks like a brecciated mass of impure opal, in which grains and crystals of feldspar and other minerals are embedded.

To the northwestward these andesites are cut off by the Cañon fault and in their southeastward extent along the head of Telegraph Cañon they become more basaltic in appearance, and it is not improbable that they actually do grade into basalts.

In the midst of this belt of andesites, at a horizon which is apparently between the flows of the holocrystalline type and those of the porphyritic type, there is a zone of lavas of quite a different character, together with a lens of tuff. These comprise basalt lavas of no great persistence in the line of outcrop and a quite thin flow of a peculiar andesite. This flow is nowhere more than 20 feet in thickness, and its outcrop on the face of the escarpment does not exceed a quarter of a mile in length. The rock is of a pale gray color, of fine, compact texture, but distinctly crystalline, and chiefly characterized by a very perfect and minute lamination parallel to the plane of the sheet. The laminæ are for the most part less than a quarter of an inch thick and quite continuous. The partings of the laminæ are accentuated by a yellowish color, apparently due to a thin film of a pale yellow crystalline substance. The rock is evidently one in which the feldspathic constituents greatly preponderate over the dark ferro-magnesian silicates.

Beds of Rhyolite Tuff.—Besides these various volcanic formations of minor extent which are included in the belt of the Grizzly Peak andesite, and which are not discriminated on the map, there are two other formations of rhyolite tuff included within the same stratigraphic limits, which, on account of the interest attaching to them, have been especially colored on the map. These also are of quite limited thickness and extent, and outcrop only along that portion of Frowning Ridge escarpment which overlooks the head of Telegraph Cañon.

The lower of the two tuff beds is at the base of the Grizzly Peak andesite belt, intervening between it and the underlying basalts. It resembles the rhyolite tuff already described as occurring lower in the section, but is much thinner, its maximum thickness being not more than about 12 to 15 feet. It is a whitish rock, in which quartz grains abound, and is distinctly stratified. It seems to increase in volume to the southeastward, and is traceable in that direction across the Fish Ranch Cañon. The second rhyolite tuff bed crops out much closer to the summit of Frowning Ridge, and it entirely crosses the ridge at a point nearly north of Summit Pass. It has the same general character as the first bed, except that it is occasionally reddish in color, and that it is perhaps even thinner.

A strong interest attaches to the occurrence of these acid tuff beds in the midst of the more basic lavas, on account of the light they throw upon the variation in the character of the magma at the center of eruption from which the lavas and tuffs emanated. They are also of interest, in the same connection, in the meagerness of their volume, as compared with the more basic lavas, and in the total absence of rhyolite lavas corresponding to the tuffs.

Fresh-water Limestone.—A fresh-water limestone also occurs as a thin bed traceable for only a few hundred feet on the top of Frowning Ridge, at a point northwest of Summit Pass. It resembles closely other fresh-water limestones, of which we shall have more to say later, being a light gray rock of compact, even texture. It is of interest as indicating a condition of fresh-water lakes in the interval between two of these flows, and that the interval was not a short one. The stratified rhyolite tuffs above referred to may in all probability have been laid down under similar lacustrine conditions.

From the foregoing statements it will be apparent that there is a somewhat varied assemblage of volcanic rocks in the belt of the Frowning Ridge escarpment which we have been discussing, but the andesites, represented in the two chief types, the holocrystalline and the porphyritic, make up the bulk of the entire volume, which is about from 450 to 500 feet. All the formations have the same general dip, to the northeastward, of about 30°.

EROSION INTERVAL BETWEEN UPPER AND LOWER BERKELEYAN.

So far as observation goes in the exposures on the face of the Frowning Ridge escarpment, we have no satisfactory evidence as to the length of the interval that elapsed between the extravasation of the underlying basalts and the rocks of the Grizzly Peak andesite belt which repose upon them; and in the absence of evidence to the contrary, we would naturally assume that the interval was not of exceptional importance. Yet it is this very interval which, as may be seen by an examination of the map, is taken as marking the break between Lower and Upper Berkeleyan. In this interval the rocks of the Lower Berkeleyan epoch were folded and eroded to a

noteworthy degree, so that the next succeeding flows of the Upper Berkeleyan period were poured out over the abraded upturned edges of the earlier formations. The evidence upon which this conclusion is based is found, in part, in a portion of the field which lies a little beyond the limits of our map on the north. Here in the bottom of Wildcat Cañon, near the "Cave rocks," and also on the county road east of the cañon, just beyond where it crosses the summit of San Pablo Ridge, the inclined beds of the Orindan formation, comprising clays, sandstones, tuffs, and limestones, some beds rich in fresh-water *ostracods*, may be seen uncomformably beneath the lavas of the Grizzly Peak andesite. The lavas repose indifferently upon the eroded surface of the various inclined beds.

Evidence of the same order is also found within the limits of the map on the north side of Baffling Gulch and on the corresponding northeastern slope of San Pablo Ridge, where the strata of the Lower Berkeleyan for a thickness of between 400 and 500 feet terminate abruptly by abutment upon the thick mass of Grizzly Peak andesite which underlies Ruin Peak. The Lower Berkeleyan strata are here evidently cut off by an old valley of erosion with rather steeply sloping sides, which at the time of the eruption of the Grizzly Peak andesite became filled with lava. The period of erosion which evolved this valley to the depth of over 400 feet and abraded the folded Orindan beds lower down on Wildcat Creek, therefore, clearly intervenes between the upper and lower divisions of the Berkeleyan.

We may now proceed with the systematic examination of our section across the Berkeley Hills.

SIESTAN FORMATION.

Change in Geomorphic Profile.—Following the same line of section as that to which we have been adhering, and which is about the same as that indicated on the map by the line C–D, we find, on arriving at the upper limit of the porphyritic variety of the Grizzly Peak andesite, that we are also at the summit or brink of the Frowning Ridge escarpment, and that we here encounter an abrupt change in the topographic profile. We pass suddenly from a precipitous slope to an almost flat shelf or terrace. We leave a

zone of beetling crags and walk over a smooth sward, where no rocks are visible. It is true, the terrace is not more than four or five hundred feet wide, but its striking contrast with the steep, rocky slopes below and above it challenges our attention; it requires but a moment's reflection to convince us that we are upon a soft formation that has succumbed to the forces of degradation to which the hard rocks on either hand are still boldly resistant.

Character of Beds.—This conviction is readily verified by a little investigation as to the character of the underlying formation. Observation on this point is possible at the head of the ravines which notch the face of Frowning Ridge escarpment, and at other places. In the middle of the terrace we meet with a pit or shaft which has been sunk in the work of tapping the water which is contained in the water-bearing strata of the hills. Around the mouth of the pit is a dump of the material which was taken from it. This dump consists chiefly of a light gray very friable sandstone with a subordinate amount of clay. In this sandstone have been found fresh-water fossils.

In the water course which drains down to the next ravine to the south into Telegraph Cañon we find exposures of blue clay and numerous fragments of a yellowish chert, such as is commonly found in other parts of the hills associated with fossiliferous fresh-water limestone. In the same water course, close to the contact with the upper surface of the andesite, there is an exposure of distinctly-stratified, peaty shales, dipping to the northeast at high angles. A little farther to the south, in the water course draining to Siesta Valley, we find excellent exposures of clay-shales with thin seams of lustrous black lignite. The stratification is well marked, and the direction of dip is the same as before, but at much lower angles. Farther down the same water course light blue clays are abundantly exposed. The evidence of repeated landsliding, which marks this end of Siesta Valley, suggests that this clay formation underlies the surface extensively. In addition to these various indications of the character of the underlying formation, we find along the base of the formation, close to the upper surface of the andesite, outcrops of a thin bed of limestone of a very light gray color and compact texture. The exposures are not abundant, and they are

best seen in the shape of a line of fragments near our line of section, and further down, in the same situation, near the southern limit of the map.

Thus, while, so far as our examination has extended, the exposures are not sufficient to reveal to us the exact relative proportions of these various deposits, we can confidently affirm that the formation which underlies the terrace is made up of soft sandstones, carbonaceous and lignitic shales, an abundance of clay, and thin beds of limestone and chert.

These various beds, and others not yet mentioned, make up the *Siestan* formation, an accumulation of deposits in a fresh-water lake which occupied the region at the close of the epoch of the volcanic activity which is represented by the Grizzly Peak andesites.

Their Extent.—In order to appreciate the essential features of the stratigraphy of the Siestan formation, it will be necessary to digress somewhat from our line of section and follow the distribution of these soft beds. It must be noted, first, however, that the clays of the Siestan formation in their northeasterly dip pass under another set of lavas. These are thick-bedded flows of basalt, the edges of which rise in an abrupt acclivity at the back of the terrace to the culminating line of Frowning Ridge southeast of Grizzly Peak.

If now we follow the outcrop of the Siestan beds to the northwest between these two sets of massive lavas, andesitic below and basaltic above, we find the terrace becoming gradually narrower and the formation thinner. In the vicinity of Grizzly Peak the terrace is little more than 100 feet wide and the underlying beds are only traceable in occasional fragments of the characteristic chert of this formation, and in the clayey character of the soil. At Grizzly Peak the terrace ends and the outcrop of the formation passes behind the peak on the northeast side. From this point onward the width of the outcrop is much attenuated, partly owing to an increase in the angle of dip of the strata and partly to a rapid thinning out of the formation. It is traceable, however, in a depression behind a line of shoulders on the northeast slope of Grizzly Peak and by occasional small exposures of the rocks themselves, up to the Cañon fault, which cuts it off.

To the southeast from our line of section the terrace loses its character as such and passes rapidly into the floor of Siesta Valley. The lower limit of the Siestan formation determines closely the southwestern edge of the valley bottom, the steep upper slopes or walls of the valley being the dip slope of the underlying lavas. This condition continues for some miles beyond the limits of our immediate field.

Synclinal Trough.—When, now, we turn to trace out the line of demarcation between the Siestan formation and the overlying basalts in the same southeasterly direction, we find that it continues parallel to the lower limit of the formation for only a short distance. About half a mile from our line of section the trace of the plane of contact between the two formations makes a sharp turn around the base of a bluff of basalt, and then bears away to the north, along the west side of the east fork of Siesta Valley. In this vicinity there are numerous excellent exposures of the Siestan beds, and from an examination of these we see that this sudden change in the direction of the contact line is accompanied by an equally sudden reversal in the direction of the dip.

The Siestan beds dip under the basalt as before but in a westerly direction. From these observations it becomes apparent that both the Siestan formation and the overlying basalts are folded in the form of a trough, and that the bluff around the base of which we have traced the outcrop of the plane of contact is the tip of a spoon-shaped area of basalt reposing on the Siestan beds. Below the tip of the spoon, Siesta Valley broadens, and its floor is underlain only by the Siestan formation, except for a line of heaps of basalt blocks extending down the middle of the valley, which are the *residua* of the former extension of the overlying basalt.

On the northeast side of Siesta Valley below the tip of our basalt spoon the Siestan beds repose, with uniform southwesterly dips upon the surface of the volcanic rocks which form the precipitous wall of the valley on this side. We thus learn that Siesta Valley is a syncline, and that the geomorphy of the valley is determined by that fact. On either side of the valley are massive volcanic flows dipping towards the center line of the valley. This center line is the axis of the syncline. Upon these lie the soft beds

of the Siestan formation, and upon them in turn the massive flows of the later basalts. The removal of the latter, except at the head of the valley, is due to the gradual sapping of the soft underlying beds, causing the formation of an escarpment, or line of cliffs, which has receded by the undermining process. That recession has gotten as far as the tip of the spoon, and the process is there still active. The sapping action is facilitated by the fact that the upper beds of the Siestan formation, being chiefly of clay, are impervious to water, so that the waters which percolate through the overlying basalts, the latter being jointed and fissured, come out at the base of the basalt in the form of springs in the synclinal axis. These springs aid materially in washing away the clay, and the basalt, thus robbed of its support, crumbles down under the action of gravity. When the front of the escarpment was farther down the valley, the springs were of course more copious in their flow than they are now, with the present limited catchment area of the surface of the basalt, so that the sapping process is less rapid than it formerly was.

Stratigraphic Asymetry of Syncline.—Having in mind the somewhat conventional ideas of geological structure that are acquired from reading and from text-book diagrams, we might expect, having recognized the general synclinal structure revealed by the erosion of Siesta Valley, that the two limbs of the syncline would be practically symmetrical. This, however, is far from being the case. Sedimentary deposits are essentially lenticular in their form and frequently thin out rapidly. It is owing to this characteristic of the beds deposited in the Siestan Lake that the northeastern limb of the syncline differs in its petrographical composition from the southwestern limb. The limestone formation, which was barely detected in a line of outcropping blocks as the basal bed of the Siestan formation on the southwestern limb, is here present, but in much stronger development, reposing directly upon the underlying volcanics. In addition to this, however, there is a second more important limestone bed fifty or sixty feet higher up in the formation. This limestone is from ten to twenty feet in thickness, and is well exposed at several places in the trench of the creek which drains the east fork of Siesta Valley.

The head of Siesta Valley, looking N. W., showing the synclinal structure of the range, Spoon Gulch in the center, Bald Peak on the right. Sheets of basalt resting upon the soft beds of the Siestan formation.

Both limestones are distinctly stratified and are locally replaced by chert. They are compact, light gray rocks of uniform texture, occasionally containing fresh-water fossils, such as *Planorbis* and *Physa*. Locally they contain numerous detrital fragments, indicating a shallow-water origin for the deposit. They can scarcely be regarded as other than chemically-precipitated deposits, although the conditions which determined the precipitation can not be stated positively.

In addition to the sandstones which were found on the southwestern limb, and which are also here represented, there are thick beds of pebbly conglomerates. These are found in immediate stratigraphic association with the limestones. Besides these, there are also beds of volcanic tuff, which, although of no great thickness, are a persistent feature of the northeastern limb of the syncline. Our former statement as to the character of the beds which make up the Siestan formation is thus considerably enlarged by an examination of these outcrops.

Northeastern Limb of Siestan Syncline.—If we follow, now, the outcrop of the northeastern limb of Siestan syncline to the northwest, we find, as soon as we climb out of Siesta Valley, that the zone of outcrops is along a shelf or terrace between two escarpments, the lesser above and the greater below, just as it is on the front of Frowning Ridge. This terrace is a prominent feature of the northeast side of San Pablo Ridge, and is in general much broader than the similar feature on Frowning Ridge, owing to the greater volume of strata on this limb of the syncline. As we follow the terrace, the exposures show that the limestones, clays, and tuffs are persistent, but sandstones and conglomerates are not in evidence. On reaching Bald Peak the outcrop bears more to the west, and the terrace passes into the bottom of a valley, a fork of Wildcat Cañon.

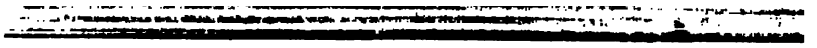
The limestones and cherts are traceable for about half a mile down this depression, and beyond that only the clays and tuffs are found to persist. The formation as a whole does not, however, diminish in volume in this direction as it does on the other limb of the syncline. Towards the outlet of Baffling Gulch extensive landslides have occurred in the soft clays just as they have in Siesta

Valley. As we descend a little farther into the broad open valley of upper Wildcat Cañon, we find that the upper basalt escarpment, which has been a persistent feature on our left to this point, abruptly stops, and that the broadening out of the valley floor is coincident with the expansion of the outcrop of the Siestan clays. In other words, we have gotten below the level of the basalts, and we turn, as we did in Siesta Valley, around the tip of a spoon-like trough of these upper rocks. It is true, the tip of the spoon is not so pointed as its analogue in Siesta Valley. It has the broad, blunted form of a scoop rather than of a spoon, but the essential identity of the stratigraphic relations in the two cases is beyond question. In the water courses which traverse this broad, flat-bottomed valley there are numerous exposures of the Siestan clays and less frequent but entirely satisfactory outcrops of the tuff beds. The upper part of Wildcat Cañon is thus, in the features described, analogous to Siesta Valley, and its geomorphic expression is determined by the same geological conditions. Just as we found in Siesta Valley fragments and patches of basalt resting upon the clay beyond the end of the basalt trough, so here we find similar residual fragments and patches of basalt in a similar situation, indicating, as before, the former extension of the basalt flows down the valley. In this case, however, the residual patches are larger and more coherent, and are mapped as a single long narrow patch. That these patches really rest upon the Siestan clays may easily be proved by finding the clays in place in the banks of the creeks below the thin veneer of volcanic rock.

Fossils.—In at least three places the trenching of these clays by the water courses has revealed fossil logs of fairly fresh or but slightly carbonized conifer timber, with bark attached. These tree trunks have a diameter of from 12 to 18 inches. The wood may be cut with a knife, burns readily, and shows no signs of silicification such as is commonly the case with timber buried in more pervious strata. In the Siestan clays to the north of Bald Peak the skull of a castoroid rodent was found some years ago, by Professor John C. Merriam, and described by him under the name of *Sigmogomphius Le Contei*.*

* This Bulletin, Vol. 1, Article 1, No. 13.

The head of Wildcat Creek, looking S. E., showing the synclinal structure of the range, the strata dipping from Frowning Ridge on the right and from San Pablo ridge on the left towards the axis of the valley. The culminating points on the two ridges are Grizzly Peak and Bald Peak respectively.



In the same bed have been found teeth of a species of *Lepus*, and the dentary bone of a species of *Lacerta*. In the clays associated with the bed in which these bones were found, occur also various molluscan forms, particularly species of *Limnæa*, *Helix* and *Ancylus*. In the limestone beds of the Siestan formation, species of *Planorbis*, *Limnæa*, and *Pisidium* occur rather commonly. Some years ago Cooper described* a few species of fossil mollusca from a locality which is rather vaguely described, but which is supposed to be the tunnel which was driven for water-supply purposes into the Frowning Ridge escarpment at the base of the amygdaloidal andesite at the head of Telegraph Cañon. This tunnel is believed to cut the Siestan beds, although this can not now be verified. The forms mentioned by Cooper are: *Anadonta nuttalliana*, Lea., var. *lignitica*, *Limnæa contracosta*, Cooper, and *Planorbis pabloanus*, Cooper.

Artesian Water.—Near the county road where it passes around the head of Wildcat Cañon a number of wells have been bored through the Siestan clay, and a supply of artesian water of moderate amount has been obtained. This of course indicates that the clay stratum prevents the escape of the underground water from the more permeable strata beneath it. The water thus accumulates in the lower beds until it establishes a hydrostatic level at a higher altitude than the surface of the ground where the wells are, and the latter, on piercing the impervious clay, permits the water to flow freely at the surface under the head so established.

Geomorphy Controlled by Structure.—In thus tracing out the distribution of the Siestan formation, we have practically encircled a long lenticular or boat-shaped area of later volcanic rocks which lie upon the Siestan beds, and have been subjected to the same synclinal folding. These volcanic rocks form the topmost part of the great stratigraphic sequence which we have been studying on our line of section along Skyline Ridge and up the western face of Frowning Ridge. The synclinal structure of these lava beds is no less marked than that of the sedimentary beds of the Siestan. Indeed, the two limbs of the syncline into which the lavas are folded are perhaps the most prominent features of the Berkeley

* Proc. Cal. Acad. Sci., Ser. 2, Vol. IV, pp. 169. 170.

Hills, since their outcrop forms the two parallel ridges which constitute their summit; and Bald Peak, the highest in the range, is part of the northeastern limb. These two culminating ridges have between them a well-marked depression in the axis of syncline. It thus appears that the morphological features of this portion of the Berkeley Hills are strictly controlled by the underlying structure.

BASALTS ABOVE SIESTAN.

These uppermost lava beds have an aggregate thickness of about 375 feet, and comprise at least three distinct flows. The lowest of the three is the most extensive, and is an iron-gray, porphyritic, olivine-basalt, which may best be studied in the excellent outcrop along the escarpment which extends from Grizzly Peak to Siesta Valley immediately above the Siestan beds. The second flow is scarcely distinguishable from the first except in the detail of surface relief, which brings out clearly the presence of two lava sheets. This flow is thus traceable in the northwestern portion of the synclinal trough, about the head-waters of Wildcat Creek, but appears to thin out to the southeastward in the vicinity of Bald Peak, so that in the Siesta Valley portion of the syncline only two lava sheets are discernible. Lying upon the common surface afforded by these two lower lava sheets is a formation of volcanic tuff of variable thickness, and in this horizon of tuff is a thin lens of fresh-water limestone, indicating the presence of lake basins on the surface upon which the tuff was deposited.

The third lava sheet rests upon this tuff and limestone, and is in general readily distinguished from the two lower flows. It has in places a rude but pronounced columnar structure, which is not apparent in the two other flows, and exhibits a more marked tendency to spheroidal weathering, the spheroids which weather out on the surface having a deceptive resemblance to water-worn pebbles. The rock is also, on the whole, coarser grained than the other basalts, and may be characterized as a dolerite or doleritic basalt.

The original surfaces of these lavas have been in places exposed by erosion, the overlying and protecting rocks having been stripped

off. These original surfaces, representing the more or less porous scum or froth of the lava, have been thoroughly oxidized, and present a reddish earthy or ocherous appearance quite different from that of the fresh compact rock beneath. Unless their relation to the main body of the lava sheet is understood, they are liable to create confusion in the mapping, by giving rise to the suggestion that they are distinct lavas.

DESCENDING SECTION ON SAN PABLO SLOPE.

Continuing our attempt at a systematic account of the sequence of formations observable in a section of the Berkeley Hills in the line of Skyline Ridge and its extension toward San Pablo Valley, it remains now to describe the formations outcropping on the northeastern side of San Pablo Ridge beneath the Siestan. The Siestan, as has been already noted, being composed of soft beds, occupies a gently-sloping shelf or terrace above the brink of a steep escarpment overlooking San Pablo Valley.

Basalts.—The basal beds of the Siestan are here limestones resting directly upon hard basalts. These basalts have a thickness of from 350 to 500 feet, and comprise several flows, which are difficult to segregate. These flows are separated by thin tuff bands or by layers of brick-red lateritic accumulations. But, although these separating lines can be made out fairly well on the shoulders of the escarpment, they can not be correlated satisfactorily across the ravines, so that the entire accumulation of lavas has been represented by one color on the geological map.

Limestone Intercalated with Basalts.—In the midst of these basaltic lavas is a bed of whitish or light gray, compact, cherty limestone, varying from 30 to 40 feet in thickness. The limestone contains fresh-water fossils identical with those in the limestone beds of the Siestan formation. These fossils have, in many cases, been completely replaced by chalcedonic silica. This limestone bed is well exposed on Eureka Peak and on the hill to the north of it. The limestone bed dips conformably with the lava sheets to the southwest, at angles varying from 30° to 60°. The presence of this thick bed of limestone, intercalated with the lava flows, is significant of an important interval, characterized by lacustrine

conditions, in the period of lava accumulation, and indicates that this period was a long one. In other sections of this same series of basalt flows the limestone bed is absent, and a consideration of these sections alone would, perhaps, lead to the erroneous view that the accumulation had been continuous and rapid.

Asymetry of Syncline.—It has been stated that these basalt sheets dip uniformly beneath the Siestan beds to the southwest, and the general synclinal structure which was recognized in the Siestan formation is here maintained. It is apparent, however, from what has been stated that the syncline beneath the Siestan beds is not symmetrical as regards the petrographical character of the lavas. On the southwest limb of the syncline the Siestan beds rest upon the Grizzly Peak andesite, while on the northeast limb, which we are now considering, they lie upon basalt, and the Grizzly Peak andesite is not represented in our section. The andesite must, therefore, thin out rapidly in the synclinal trough; and the basalts underlying the Siestan on the front of San Pablo Ridge are correlated with the basalts underlying the Grizzly Peak andesite on the front of Frowning Ridge. These basalts are much thicker on the San Pablo side than on the Frowning Ridge side, indicating that they thin out to the southwest. This petrographically asymmetric character of the syncline is true of other formations of the series and arises from the conditions of accumulation of the strata. Lavas generally flow down valleys, and, if the valley is a wide one, are likely to occupy one side of the valley, being thickest in the line of flow and tapering off towards the sides. A valley thus partially occupied by a congealed lava stream would have its drainage line displaced to the other side, and a succeeding lava stream would follow the new drainage line. It would not be directly superimposed upon the earlier lava, although it might overlap it to a large extent. Such appear to have been the general conditions attending the accumulation of the lavas in the region now occupied by the Berkeley Hills. It must, therefore, occasion no surprise to find that, although the syncline in a structural sense is perfectly symmetrical, the formations outcropping in the two limbs are not always persistent across the fold.

Andesite, Conglomerate, and Tuff.—Following our general section down the San Pablo slope, we find beneath the basalts a sheet of andesite having a southwesterly dip and an average thickness of perhaps 100 feet, although locally much thicker. This sheet is quite persistent in the line of strike, but seems to thin out in the synclinal trough, and does not appear on the Frowning Ridge side. Beneath this we find a formation of conglomerates and tuffs, with a maximum thickness of 500 feet, which seems to correspond with the much smaller volume of tuffs immediately above the amygdaloidal andesite on the Frowning Ridge side of the syncline. This formation yields a heavy soil, rich in well water-worn pebbles of small size, and it is only in certain stream cuts that its composite character can be made out and beds of tuff discriminated from the conglomerate. A portion of the matrix of the conglomerate is probably also tuffaceous.

Amygdaloidal Andesite.—Beneath these conglomerates and tuffs lies a sheet of amygdaloidal andesite, dipping southwesterly or into the ridge. This lava is identical petrographically with the amygdaloidal andesite at the base of the volcanic series on the opposite limb of the syncline, and is here also the earliest flow. We have, therefore, good reason for correlating it with the amygdaloidal andesite first met with in our ascending section. It is the most uniformly characterized of all the lavas we have to deal with, not only in its petrographical character, but also in its thickness, and it is at the same time the most extensive. The ease with which it may be identified renders it, next to the Siestan formation, the most reliable stratigraphic element in the deduction of our conception of the synclinal structure.

Orindan Formation.—Just as on the opposite limb of the syncline, this amygdaloidal andesite here lies upon the gravels of the Orindan formation. On this side, however, the Orindan formation is much thicker and somewhat more varied in its stratigraphic composition than it is on the upper slopes of Strawberry and Telegraph Cañons. In this respect we have another illustration of the lack of symmetry in the formations thus synclinally folded. The maximum thickness of the formation is much greater than that exposed on Skyline Ridge but need not here be stated with pre-

cision. It will be sufficient to say that we do not reach the base of it even when we descend to San Pablo Creek, and that it reposes unconformably upon the Monterey formation in the hills on the east side of San Pablo Valley. As we follow the Orindan formation thus easterly, we find it not only thicker but affording evidences of a deeper water sedimentation. Conglomerates still form a large proportion of the whole accumulation, but there is a larger proportion of evenly-bedded and finer-grained sandstones, shales, and clays. There are also several thin beds of limestone and thin beds of dark volcanic tuff intercalated with the shale and clay beds, which are not represented on the southwestern limb of the syncline. The fine-grained sandstones, shales, clays, and limestones are characterized, as has before been stated, by an abundance of fossil fresh-water ostracods,* and these crustaceans are practically the only invertebrate fossils which are known to occur in these rocks.

Subordinate Flexures.—The Orindan beds beneath the amygdaloidal andesite when we first meet them in our descending section on the slopes north of Eureka Peak, dip to the southwest conformably with the sheet of andesite. But the dip rapidly changes, as may be readily observed in the excellent exposures on the north side of the first ravine north of Eureka Peak. The stratified gravels are here seen in the face of the bluff to pass from a southwesterly dip to a northeasterly, forming a perfect anticlinal arch. From the crest of the arch the overlying andesite has been almost entirely removed, leaving only a residual patch a few yards in extent. The dip on the northeastern limb of the anticline conforms closely to the slope of the hill, but is sufficiently steep to again carry the conglomerate beds beneath the andesite. This anticline is quite a minor feature compared with the great syncline which dominates the structure of the Berkeley Hills. It is, however, longitudinally persistent along the entire slope within the limits of our map.

Immediately to the northeast of this anticline there is another shallow syncline of still less importance than the anticline. It is

*See Bull. Dept. Geol. Univ. Cal., Vol. 2, No. 2, on *Some Pliocene Ostracoda from Near Berkeley*, by Frederick Chapman.

best seen in the sections afforded by Tumbling Brook, on either side of which it may be traced for a short distance. In the trough formed by the gently-folded andesite lies a remnant of the formation of conglomerate and tuffs which regularly lies above it in the main section of the upper slopes. A glance at the map will indicate the disposition of the rocks in this syncline better than any detailed description. No other folds are known to affect these strata; and beyond the edge of the last-mentioned syncline, as marked by the most northeasterly outcrop of the amygdaloidal andesite, we have only southwesterly-dipping strata of the Orindan formation to its base, where it rests on the Monterey on the far side of San Pablo Valley.

Transverse Fault.—In mapping the outcrop of the various sheets of rock, both volcanic and sedimentary, on the northeast slope of San Pablo Ridge, their continuity is found to be distinctly interrupted along a line which runs northerly from the saddle near Eureka Peak. The same strata may, indeed, be found again on the other side of this line, but when the various strata are carefully traced out and plotted accurately upon the map, it becomes very apparent that they have all suffered a dislocation in the same direction along the line indicated. The dislocation, moreover, appears upon the map to be a horizontal one, the strata on the west side of the line being uniformly displaced several hundred feet to the north relatively to the strata on the east side. This appearance of the map is the best possible evidence of a *fault*, the trend of which is transverse to the strike of the rocks. The fault *may* have actually differentially displaced the strata, as it appears to do on the map, by a horizontal movement, but a little reflection will show that, inasmuch as we are here dealing with the limb of a syncline in which the strata are dipping into the ridge, the same appearance might be effected by a *vertical* displacement, which would cause a wider portion of the syncline to drop down opposite a narrower lower part. Since vertical displacements on a fault plane are very much more common than horizontal displacements parallel to the strike of the fault plane, it is probable that we are here dealing with a vertical dislocation. The apparent horizontal displacement is, therefore, really the heave of the fault, and, knowing the amount of

the heave and the dip of the strata, the throw of the fault may be calculated. The throw of the fault, where it dislocates the amygdaloidal andesite, thus estimated is not more than 150 feet, although the heave is nearly 500 feet. This fault not only traverses this limb of the dominant syncline of the Berkeley Hills, but also the subordinate flexures of the lower portion of the San Pablo slope, as is indicated on the map, and is in part responsible for the somewhat complicated appearance of the map in this region.

There is also a slight dislocation of the strata on the summit of Frowning Ridge just north of the Summit Pass, and also evidence of faulting at the lower end of Spoon Gulch, and as these are in the same general line as the dislocation on the San Pablo slope, they may be regarded as part of the same general fault, and they have been so indicated on the map. It is to be noted, however, that the downthrow of the fault on Frowning Ridge is on the east side of the fault, whereas, as we have just seen, the downthrow on the San Pablo slope is on the west side. This of course tends to cast doubt upon the supposition that the two dislocations occur upon the same fault plane; but it is believed that within the limits of the movement there might easily be sufficient inequality of displacement to allow of such a discrepancy.

Intrusive Dolerite.—On the north side of Orinda Hill and in the vicinity of Tumbling Brook there are indicated upon the map some areas of dolerite. Although the relations of this rock to the Orindan formation can not be made out as clearly as could be desired, yet the fact that their distribution shows them to be discordant to the adjacent rocks, and that they appear at different horizons, indicates that they are intrusive masses. The rather coarse holocrystalline character of the rock and its petrographical identity with a clearly-marked dyke in a part of this same field beyond the limits of the map, support this conclusion.

THE CAMPAN SERIES.

Limits of Basin.—The Berkeleyan series, although representing in its accumulation of varied sedimentary and volcanic rocks, in the recognizable intervals of non-accumulation between these, and in the deformation of series as a whole, a long and important epoch

in the geological history of the Coast Ranges, does not embrace all of the Pliocene formations of the Berkeley Hills. Even within the small area covered by our map there is a later and scarcely less important basin of rock accumulation, which is also referable to the Pliocene. This basin lies to the west of the Cañon fault, and on the north side of Strawberry Cañon, extending thence northwesterly beyond our map with an expanding area. The southwestern limit of the basin, as left to us by erosion, is the exposed line of contact of its basal beds upon the sandstones of the Shasta-Chico. This line extends from near the southeast corner of La Loma Park across Wolsey Cañon and Serene Hill down to the bottom of Strawberry Cañon near Such's ranch. This line of demarkation converges upon the Cañon fault, as may be seen upon the map, towards the southeast, so that the area with which we have here to deal is wedge-shaped, the point of the wedge being in Strawberry Cañon at the base of Monument Hill.

Within the area thus defined we have a post-Berkeleyan accumulation of fresh-water beds and volcanic lavas and tuffs to an aggregate thickness of about 800 feet, and it is probable that a considerable fraction of the original volume has been removed by erosion.

This series of formations is designated the Campan series because of its occurrence within the limits of the University Campus. Owing to the lenticular character of some of the formations of the Campan series and the limited extent of others, it will be inexpedient to limit our inquiry to any particular line of section. The different formations will be described briefly in ascending sequence, and reference will be made to various sections and exposures at which the observations here recorded may be verified. The smallness of the part of the basin with which we are here concerned also renders a comprehensive account of the formations more appropriate than an account of individual sections.

The lowest and most important sedimentary member of the Campan series consists chiefly of a formation of lacustrine conglomerate, intercalated with which are beds of light-colored and red clay-shale, sandstone, and limestone, and occasional admixtures of volcanic tuff, the entire formation having a thickness of about 250

feet in Strawberry Cañon. These beds lie upon the upturned and abraded edges of the rocks of the Shasta-Chico, Monterey, and Berkeleyan series indifferently. The only exposure of the base of the formation is along the southwestern limit of the Campan basin from the ravine at the southeast corner of La Loma Park to Such's ranch in Strawberry Cañon. Along this line the formation rests directly upon the surface of the sandstones of the Shasta-Chico series, except for that small portion of it which lies between the south and middle forks of Strawberry Creek, where a patch of the Monterey chert and shale formation intervenes between the Campan and the Shasta-Chico. The entire contact is one of marked unconformity. No single bed of the formation can be traced out continuously along the contact upon the older rocks, owing to the softness of the beds and the readiness with which they break down into soil. There are, however, numerous exposures of clay shales, thin beds of limestone, and thick beds of conglomerate, and the Shâsta-Chico sandstones are generally easily recognizable as soon as one leaves the higher formation, so that the contact is nowhere indeterminate. It is, moreover, indicated by a line of change in the profile of the hills. The best exposures of the limestone beds are in Wolsey Cañon in the line of the creek and on the summit of Serene Hill on the University Campus. The beds are thin, probably not exceeding six inches in thickness. The rock has the same compact texture and light-gray color which characterize the fresh-water limestones of the Berkeleyan series. No fossils have, however, as yet been found in it. The shales are most abundantly exposed in Wolsey Cañon, and they are well known from well borings to underlie the grain field between the south and middle forks of Strawberry Creek, on Such's ranch. Above the basal beds the formation is chiefly conglomeratic, but beds of sandstone also occur and are well exposed in the gulch to the southeast of Fog Bluff. In the upper portion of the same gulch there is an exposure of some twenty or thirty feet of red clays and clay shales. There are good exposures of conglomerate, part of it admixed with volcanic material, in the vicinity of Such's ranch-house. For the most part the conglomerate yields a soil full of water-worn pebbles,

The Berkeley Hills, looking S. E. from Little Grizzly. The series of rounded hills in the middle of the picture is the outcrop of the Monterey cherts and shales; at their base on the right is the Cañon fault. The terrace on the left is underlain by the soft Orindan beds and is due to differential degradation.

so that even where there is no distinct outcrop of the strata, the nature of the underlying formation is in this case revealed.

This line of contact between the base of the Campan series and the older rocks is interrupted by a fault in the line of the north fork of Strawberry Creek, and it finally abuts squarely upon a more important fault in the line of the south fork, and beyond this latter fault the Campan formation does not extend. This fault has a downthrow to the north of not less than 600 feet as measured by the fact that the Campan beds, which must originally have had a position above the level of the crest of Skyline Ridge, are let down so as to abut upon the base of its north flank. This fault, thus chopping off the extension of the Campan formation, serves as its southern boundary for a distance along Strawberry Creek of about 1,150 feet, to a point where it intersects the Cañon fault. From this point the Cañon fault serves as the eastern limit of the basal formation of the Campan series. The Campan beds have been let down by this fault against the cherts and shales of the Monterey series and against the various members of the Berkeleyan series which enter into the structure of Frowning Ridge. It is the relationship of the Campan beds to the Monterey and Berkeleyan formations which proves the direction of the downthrow for this fault, a question which could not be conclusively settled by the facts observed on Skyline Ridge alone.

The Cañon fault may be traced very definitely to a point in the upper part of Wildcat Cañon, about 1,100 feet north of the summit of Little Grizzly. At this point the base of the fault plane appears to pass beneath the overlying Campan beds, but emerges from beneath them again two-thirds of a mile distant, in the same general direction, again faulting the lower Campan beds down against the Berkeleyan rocks.

Diastrophic Trough.—Thus far, in speaking of the Campan series, we have referred to it as a basin, but as regards the basal formation it will be evident from what has been stated above, that it in reality occupies a disastrophic trough. One side of the trough is the steeply-inclined plane of the Cañon fault; the other side is the gently-inclined pre-Campan surface, sloping northeasterly till it intersects this fault. The general dip of the forma-

tion is towards the fault, as the mapping in Strawberry Cañon clearly shows. This trough is cut off, as has been already pointed out, by the important fault in the line of the south fork of Strawberry Creek, which was probably synchronous in formation with the Cañon fault. The effect of these two faults was to drop a block or wedge of the early Campan basin down into the surrounding country. In this fact we have the key to the geomorphogeny of Strawberry Cañon; for the diastrophic trough thus formed continued to be a basin of accumulation, and the formations there deposited, as well as those originally faulted, proved subsequently to be much more susceptible to erosion than the rocks of the Shasta-Chico and Monterey series, which hemmed them in on all sides; so that when Strawberry Creek reached them in the normal process of head-water erosion, it rapidly worked out of them a wide amphitheater-like, subsequent cañon, while the consequent gorge is still constricted.

Probable Volcanic Vent.—At the quarry a little north of Such's ranch-house there is a small area of volcanic rocks entirely surrounded by a gravel conglomerate. It is about one and one-quarter acres in extent. The quarry has cut into the mass to a depth of about thirty feet, and in the bottom of the quarry there was at one time a well to a depth of about twenty feet. These excavations have revealed very clearly the character of the rock. It is of a mixed character, being partly a vesicular basalt and partly an agglomerate. The two are intimately mixed and the agglomerate blocks are frequently large. The isolated occurrence of the mass and the character of the material strongly suggest that we have here one of the minor vents from which emanated some of the later lavas and tuffs. The more or less open character of the rock has permitted percolation of waters, so that the entire mass is rather oxidized and ocherous. Small seams of calcite also occur in it, and, what is more interesting, occasional deposits of asphaltum in irregular spaces not exceeding a cubic centimeter in size.

The small area of basalt to the southwest of Such's ranch-house evidently owes its position to the fact of its having been dropped between two converging faults, alluded to above and indi-

cated on the map. Its relations to the conglomerate are, however, obscure, and it is doubtfully correlated with the basalt of Gopher Ridge, which it resembles, although it may with equal probability be intrusive.

Lake Beds and Lavas.—Prior to the faulting which converted the Campan basin into a diastrophic trough, the infilling of the basin by sedimentary deposits was several times interrupted, or rather supplemented, by flows of lava and extravasations of tuff. The proof of this is seen in the sheets of lava and tuff which are interleaved with the sedimentary strata in the vicinity of Pie Knob and Fog Bluff and in the intervening Wolsey Cañon.

The earliest of these lavas are those best seen on the lower flanks of Fog Bluff and on Pie Knob. There appear to be at least two flows representing this stage of volcanic activity, which can not be discriminated sufficiently well for separate mapping, so that, although the two rocks are quite different in appearance, they are mapped together as andesite, to which type they may both be referred. The lower is a dark rock, readily decomposed, of open texture and frequently vesicular or amygdaloidal. This rock probably underlies Fog Bluff and occurs as a series of outliers on the lower Campan conglomerate on the slopes south and west of Fog Bluff.

Above this dark andesite is a light-colored lava which is in marked contrast to the lower rock. Typical specimens are of a light gray to reddish-gray color, compact to porous in texture, and have a strongly-defined flow lamination. The rock is resistant to disintegration, and differential erosion brings it out in bold relief. It is owing to this quality that it has found favor to some extent as a road metal for the streets of Berkeley. The rock is microcrystalline, and phenocrysts are only occasionally observable.

The porous varieties of the rock frequently show distinct openings along the planes of lamination, and seams and films of hematite and limonite are found in these openings. The absence of the ferro-magnesian silicates is a characteristic of the rock in its macroscopic aspects, the rock being almost wholly feldspaltic. These andesites have a maximum thickness in the Pie Knob section estimated at 180 feet. On the north side of Wolsey Cañon they

dip at low angles into the hill or northeasterly, while on the south side, on the flanks of Fog Bluff, the same flows dip southwesterly. This fact, taken with the very apparent dislocation of the strata on the line of Wolsey Cañon, establishes clearly the fact of a fault along that line.

Above these andesites is a formation of conglomerates and red clays having a thickness of about 200 feet in the Pie Knob section, but thinning out rapidly towards Fog Bluff and towards the northwest. They have the same dip and were affected by the same faulting as the andesites below them. The presence of these beds clearly indicates the resumption of the lacustrine conditions for a considerable time after the outflow of the lower andesites. The formation is best seen in the sections on the north side of Wolsey Cañon, in the ravine to the east of Pie Knob, and in the quarry at the north end of Pie Knob. On the southwest side of Fog Bluff, where the rocks dip down the slope, their presence is indicated by a heavily-soiled shelf and by the presence of pebbles in the soil.

Above this formation is another sheet of andesite lava about seventy feet thick. This forms the summit or cap of Fog Bluff except for a few small residuary patches of fresh-water limestone which rest upon and adhere to the upper surface of the lava. This lava sheet is rather decomposed, and is in places oxidized and ocherous. It, also, has been dislocated by the Wolsey Cañon fault, and beyond the fault to the northwest is traceable to the quarry at the north end of Pie Knob and beyond. Still another small lens of andesite lava lies above this to the east of Pie Knob.

Even these lavas did not displace the Campan Lake, for we find above them still later beds of conglomerate and clay which appear to be traceably continuous with the main body of the lower Campan formation, indicating that these various volcanic effusions effected merely a local interruption in the deposition, and that the process of sedimentation in the basin was continuous.

Above these conglomerates and clays is another thin sheet of lava which in the line of outcrop is discontinuous and which has the character of a transition from basalt to andesite and is classed on the map as an andesitic basalt.

Period of Faulting.—Up to this stage all the strata, whether

sedimentary or interleaved volcanic, have been dislocated by the Wolsey Cañon fault. But the rocks above this show no evidence of faulting, and the trace of the fault plane appears to pass beneath these higher formations at the head of Wolsey Cañon. There is evidence, moreover, that it appears from beneath the same formations again on the far side of Gopher Ridge, in the upper part of Wildcat Cañon, as the mapping indicates. But this is precisely the same horizon at which the Cañon fault described on a previous page, passed beneath the higher formations of Gopher Ridge. It would seem, therefore, that the Cañon fault and the Wolsey Cañon fault occurred at the same time, and we are thus able to define narrowly the exact stage in the accumulation of the Campan series at which the Campan basin was converted into a dislocated, diastrophic trough.

These two faults intersect at a point about 1,250 feet north of Little Grizzly Peak, beneath the mantling formations, and at this point there is a curious sink-like depression in the hillside, as is indicated by the contours of the map. The depression resembles a landslide in certain of its features, but the evidence that it is a slide is not satisfactory, and it is not improbably a sink of the surface due to the more recent movements of these intersecting faults.

Later Accumulations.—After these disturbances the accumulation, both lacustrine and volcanic, continued, and there remain to be considered three distinct formations to complete what is left of the record of the uplifting of the Cañon trough. These are a thick bed of basic volcanic tuff with some conglomerate, a series of basalt flows, and a rhyolite agglomerate and tuff.

Between the period of disturbance and these later additions to the accumulation there was, however, an interval of erosion in which the inequalities due to the faulting were in some measure reduced, particularly where the faults affected the softer formations. This is inferred from the comparatively even surface upon which the formations mantling the fault repose. In other places, as on the north side of Strawberry Cañon, the lowest of the three formations which succeeded the faulting is locally much thicker than elsewhere, as if it occupied a ravine in the surface upon which it was deposited.

This earliest of the three formations in question is essentially a volcanic tuff. It is, however, locally admixed with gravel and contains a small lens of limestone and several small lenses of basaltic lava. The tuff is for the most part decomposed and presents usually a yellowish or dark brown appearance. It is generally free from quartz, and is evidently the product of a basic or at least andesitic eruption. This formation presents numerous exposures on the slopes on either side of Gopher Ridge, below Little Grizzly and below Rough Hill. It has a maximum thickness of about 200 feet, and varies from this down to less than twenty feet, the difference in volume being apparently due, as has been above suggested, to the inequalities of the surface upon which it was deposited. In good exposures the formation is seen to be evenly stratified and occasionally is fairly well indurated so as to present outcrops in the form of steep bluffs, as in the section to the northeast of Pie Knob. In this section a considerable fraction of the entire volume of tuffs, towards the upper part, is rhyolitic in composition.

After the deposition of these tuffs the accumulation of the Campan gravels was resumed, at least in the northwestern part of our area. Here we find a wedge of gravel conglomerate intervening between the tuffs and the overlying basalts, while on the slopes of Strawberry Cañon and Wildcat Cañon the basalts repose directly upon the tuffs.

The overlying basalts make up the greater part of the surface of Gopher Ridge, and a portion of the lower slopes of Rough Hill in Wildcat Cañon. Some outlying patches of the same basalts occur near the county road on both sides of Wildcat Creek below the bridge. The basalts lie usually upon the tuffs, or upon the wedge of gravel conglomerate above referred to, but they also extend beyond the limits of this formation and rest partly on the clays of the Orindan formation and partly upon the Grizzly Peak andesite in situations which may be readily ascertained by a glance at the map. It is probable that the tuffs were subjected to erosion prior to the outflow of the basalts, so that the limits of the tuff formation, where transgressed by the lavas, are not necessarily the limits of the basin in which it was deposited.

Little Grizzly. A near view of the rhyolite flow and agglomerate which forms the highest member of the Cascade Series.

It is practically impossible to say how many flows are represented in the basalt formation, but, judging from the variation of petrographic character and the presence of certain brick red deposits, probably lateritic, there must be several flows. These have a maximum aggregate thickness of about 350 feet towards the south and thin out to the north, so that beneath the rhyolite agglomerate of Rough Hill the thickness does not exceed fifty feet.

The latest formation is a light-colored, strongly-cemented agglomerate and tuff, of which only residuary patches remain to us. From the nature of this formation it is certain that it must have at one time extended in a continuous sheet over a large part of the area of the Berkeley Hills. At present it is represented by ten small isolated areas, of which six do not exceed an acre in extent. The largest of these remnants and the most instructive for study is that which occupies the greater part of Rough Hill. Here it is about 100 feet thick, and shows only occasionally evidences of stratification. It is a typical coarse fragmental rock of volcanic origin. It presents bold and rocky outcrops, broken, by surface disintegration, into large slabs and rounded, boulder-like masses, the surfaces of which are studded with angular knobs and irregular protuberances caused by differential weathering. On fresh surfaces the rock is yellowish white, gray, or green, varying according to the degree of oxidation. A light-colored, fine-grained paste incloses fragments of quartz and feldspar and sharply-angular fragments of various rocks of all sizes up to six inches in diameter. This ground-mass may be seen with a lens to be heterogeneous in composition and to be made up of finely-comminuted and sharply-angular fragments of rocks and crystals. The abundance and large size of the fragments in certain beds show that the vent from which they were ejected could not have been far distant. The location of this vent is, however, at present unknown.

The other smaller patches represent only the basal portion of the formation, and are in general not so coarse-textured, the angular blocks of lava being usually not greater than an inch or two in diameter. There are, however, no other important differences. These patches do not all, however, repose upon the basalt. Two of them lie across the line of demarkation between the basalt and

the underlying Campan conglomerates, and two lie entirely within the area of these conglomerates, reposing directly upon them. Four rest on the basalt alone, viz., that which forms the summit of Little Grizzly, the area about 1,500 feet to the west of this, one on the western flank of Gopher Ridge, and one on the north slope of Rough Hill. The smallest area lies above the county road on the east side of Wildcat Creek. It rests upon a small area of basalt, and the latter directly upon the Grizzly Peak andesite, the older formations of the Campan series being wanting.

The distribution of these various residuary patches of this rhyolite agglomerate and tuff show that the underlying basalts had been subjected to extensive erosion before its deposit. The basalt was undoubtedly originally much more extensive than it now is, and yet its present boundaries were approximately defined by erosion before the accumulation of the agglomerate and tuff above it. We are, therefore, warranted in the inference that a long interval of time intervened between the two extravasations.

Later Faulting.—Since the deposition of the agglomerate and tuff formation, the Campan trough has again been disturbed and broken by faults. Two of these faults are important structural features of the Campan series. One serves as the northern limit of the Rough Hill area of agglomerate, the latter having been dropped below the basalts against the tuffs which underlie them. The other serves as the northern limit of the Campan volcanics, these having been dropped on the south side of the fault against the underlying Campan conglomerates. This fault appears to swing around and to be continuous with the fault which dislocates the Campan volcanics and sedimentary beds to the east of Pie Knob as it is indicated on the map. Other small faults to the south of Pie Knob, rendering the structure complicated and giving character to the geomorphy, are probably of the same age as these two larger faults.

This summary account of the formations which make up the Campan series, as left to us by erosion, suggests the possible existence of still other formations once above the rhyolite agglomerate but now entirely removed. The fragmentary condition of the latter formation, although comparatively hard and resistant to

disintegration, is ample evidence of an erosion interval competent to remove not only nearly all of the once extensive rhyolite agglomerate but also the whole of other formations which may have reposed upon it.

RELATIONS OF CAMPAN AND BERKELEYAN SERIES.

Post-Berkeleyan Deformation and Erosion.—It has been shown that the Berkeleyan series of sedimentary beds and lavas occupies a great synclinal trough, with some subordinate parallel flexures. The development of this structure was probably inaugurated at the close of the Lower Berkeleyan, for we have seen that the discrimination between Upper and Lower Berkeleyan is based upon the recognition of the deformation of the Lower Berkeleyan, and the erosion of the beds so deformed before the accumulation of the Upper Berkeleyan beds and lavas upon them. It was, however, of course not till the close of the Upper Berkeleyan that the synclinal structure was fully established, although it was probably in progress of development during the Upper Berkeleyan epoch, as is indicated by the persistence of the trough conditioning the *locus* of accumulation, and by the somewhat steeper dip of the lower beds as compared with that of the upper.

Stratigraphic Unconformity.—The stratigraphic relations of the Campan beds and lavas to this great syncline are clear. The Campan trough is discordant both in strike and dip to the Berkeleyan strata. In simpler terms, it lies across the edges of the Berkeleyan syncline. There is, therefore, an unconformity between the two series. The mere discordance of the beds might, however, be in part explained by the operation of the cañon dislocation. A study of the situation shows, however, that while that fault accentuates the discordance, it neither masks nor adds to the true unconformity if properly discriminated from the other structural features. The Cañon fault when it dropped the lower part of the Campan strata against the Berkeleyan, undoubtedly carried down out of range of present observation the northwest end of the Berkeleyan synclinal trough, since the fault cuts obliquely across the axis of the syncline. But since neither the Berkeleyan nor the Monterey rocks appear again from beneath the Campan on

the western flank of the Berkeley Hills north of Berkeley, it is clear that before the formation of the Campan trough the Berkeleyan syncline had been so reduced by erosion that it had feathered out, somewhere between the line of the Cañon fault and the present front of the Berkeley Hills, where we find the Campan beds resting directly upon the sandstones of the Shasta-Chico series. In this fact we have a measure of the unconformity. Not only was the time interval between the Berkeleyan and the Campan sufficient for the great orogenic deformation exhibited by the Berkeleyan syncline, but also for the degradation of that syncline, so that the Campan trough was established across the worn edges of the northwest end of the tapering, canoe-shaped structure. We may, therefore, safely conclude from these considerations that the Campan trough, or basin of accumulation, was long subsequent to the Berkeleyan epoch, and that the interval between the two epochs was probably not less important in the geological evolution of the Coast Ranges than those epochs themselves, although it is not represented in this region by strata.

It is not clear whether the Campan basin was originally a diastrophic trough or merely an ordinary valley of erosion which had become dammed, owing to some geological accident, such as its partial occupation by lava. But inasmuch as the Cañon fault clearly made it a diastrophic trough, it is a fair hypothesis to suppose that the forces which culminated in that dislocation had previously been active, and that the original depression was due to local deformation.

Deformation of Campan and Berkeleyan Contrasted.—The contrast in the character of the deformation of the Berkeleyan and Campan rocks is interesting. The Campan basin, like the Berkeleyan, has been folded synclinally, but the flexure is much more gentle. On the other hand, the Campan basin is much more broken by faults than is the Berkeleyan, and it is probable that most, if not all, of the faulting of the region took place either during the Campan epoch or subsequent to it. Inasmuch as the rocks occupying the two basins are very similar, we must ascribe the difference in the condition of deformation to some other than a petrographical cause. One general difference in the character of

the two basins is pertinent to this question. It is that the constituent members of the Campan series are much more lenticular than in the Berkeleyan. The interdigitation of these rather thick lenses would imply of course considerable differences in the strength of the aggregate when subject to stress. The stronger portions of the basin might be flexed, while the weaker portions broke and slipped. The comparatively persistent and regular strata of the Berkeleyan conduced simple flexure. The faulting is most abundant in the Campan basin where the lenticular character of the constituent members is most pronounced. Another consideration may be referred to. It is possible that the Berkeleyan series may have been more deeply buried, by other rocks now removed, at the time of its deformation, and so have been constrained to yield in a plastic manner to deforming stress, while the Campan rocks, being probably nearer the surface at the time of their deformation, would have been more liable to yield to similar stress by fracture.

It is to be noted, however, that the dominant fault of the region, the Cañon fault, is not a compression fault but is a gravity or normal fault. We have exemplified, therefore, in this region, an alternation of compressive stress resulting in flexure and thrusting, and gravitative stress resulting in normal faulting. The cause of this alternation of the direction of stress exemplified in so many disturbed regions is one of the most fundamental problems in orogeny, and still awaits a satisfactory solution.

It is further worthy of note that during the deformation of the Campan the Berkeleyan syncline acted as a resistant buttress against which the Campan basin was flexed and broken.

MICROSCOPIC PETROGRAPHY OF THE VOLCANIC ROCKS.

THE ANDESITES.

The andesitic rocks present a very uniform mineralogical composition, and may all be classed as pyroxene andesites. Structural variations are, however, both numerous and well defined, and it

will be convenient to describe the various forms under separate heads, designating each by a term descriptive of its structural peculiarity. The most typical of these facies will be known as, 1st, the amygdaloidal facies; 2d, the porphyritic facies; 3d, the holocrystalline laminated facies; 4th, the aphanitic laminated facies. To avoid unnecessary repetition, the minerals composing the rocks will first be described, and then the rocks in their various forms will be considered.

Constituent Minerals.—The andesites are composed essentially of plagioclase feldspar and augite. In addition there occur as accessory constituents in varying amount, orthoclase, hypersthene, olivine, apatite, and portions of glassy base. The secondary minerals include serpentine, chlorite, calcite, iron ores, chalcedony, opal, quartz, analcite, and natrolite. Plagioclase feldspar occurs in two generations. The porphyritic crystals are generally of idiomorphic outline, in stout to long prismatic forms. They vary in size from the smallest dimensions up to a quarter or half inch in length. Frequently several crystals occur in juxtaposition, forming allotriomorphic aggregates or groups of crystals whose outer boundaries only are idiomorphic. The feldspars are clear and glassy, and exhibit distinct cleavage cracks and irregular shrinkage cracks in abundance. Measurements of extinction angles on sections of albite twins whose alternate lamellæ extinguished symmetrically on the trace of the twinning plane, gave maximum results varying from 13 to 32 degrees. As the angles from 13 to 23 degrees were obtained from the feldspars of one facies of the andesite, and those from 24 to 32 degrees from the feldspars of another facies, it is probable that the plagioclase is of variable composition, but it is all embraced within the limits of the labradorite group. Twinning after the albite law is the rule, sections of phenocrysts which showed no twinning lamellæ being very exceptional. The lamellæ vary much in breadth and number, but seem to hold a somewhat constant relation to the size of the crystal, the largest crystals having the fewest and broadest lamellæ. Twins formed according to the pericline law and the carlsbad law were also observed in a few crystals. Zonal structure is very common in the feldspars. The zonal bands are sometimes broad and

distinct, but more usually zoning is merely evidenced by undulatory extinction. In all observed cases the inner portion of the zoned crystals extinguished at a higher angle to the axis of elongation than the peripheral portions. Many crystals which appear quite clear reveal under high powers the presence of clouds of minute dusty bodies which are scattered irregularly through the mass of the crystal, and are wholly undeterminable. In addition to these, which seem to be always present, are found inclusions of glass, augite and its alteration product, serpentine, magnetite, and apatite. The distribution of these inclusions is exceedingly irregular, but as a rule the largest phenocrysts show them more characteristically. The glass occurs in irregular branching areas, or in rounded blebs sometimes containing a black-bordered gas bubble. It is brown to black in color and generally crowded with dusty black specks, probably of magnetite. It is most common in the phenocrysts of glassy facies of the rock, but also occurs in holocrystalline forms. Augite forms rounded grains or branching patches sometimes so numerous as to nearly equal in bulk the mass of the feldspar host. No order is perceptible in their arrangement with reference to one another, but they are sometimes grouped more or less regularly with reference to the boundaries of the host. This grouping is either in a sharply-defined central zone, in a narrow peripheral zone, or in an intermediate zone with clear spaces within and without. In one or two instances only were the augite inclusions seen to have a uniform orientation over considerable spaces, giving rise to an appearance of micropegmatitic intergrowth. The decomposition of these augite inclusions to serpentine is common, and the increased bulk of the mineral causes it to migrate into the cracks and cleavages of the host. The appearance of these augite inclusions is perfectly represented in the figure in Rosenbusch Mik. Phys., Plate XXIV, fig. 3, although in that plate the inclusions are of glass. Magnetite and apatite occur in characteristic forms in greater or less abundance without definite grouping. Movements of the unconsolidated magma are evidenced by numerous cracked and broken crystals, their fractured surfaces separated by bands of intruded ground-mass. Corroded phenocrysts are also seen, and occasionally the shadowy outline of

crystals can be detected whose entire substance has been replaced by the ground-mass of the rock. Decomposition has affected the feldspars of these rocks in a very slight degree. On weathered surfaces they sometimes become opaque and earthy, but in the thin sections studied, the traces of decay were hardly noticeable. In fact, the feldspars seem frequently the last elements of the rock to yield, for specimens were collected in which the ferro-magnesian silicates were completely decomposed, leaving the rock a crumbling mass, and yet the feldspars appear fresh and glassy. In one instance, replacement of feldspar by analcite was observed, and will be described under that mineral.

The feldspars of the ground-mass are both microlitic and granular in habit. Lath-shaped microlites are most common, and exhibit the uneven boundaries and irregular terminations common to the ground-mass feldspars of andesitic rocks. They are generally twinned, and, like the phenocrysts of similar composition, are clear and glassy, rarely showing signs of decay. Judging from the extinction angles, they have the composition of oligoclase, more rarely of labradorite.

The presence of orthoclase feldspar in the andesites is considered probable but was not demonstrated. Certain phenocrysts showing no twin or zone structure, and free from the ordinary inclusions of the plagioclase crystals, are believed to consist of this mineral. The repeated occurrence of such crystals in the slides and the presence of a considerable amount of potash in the rocks, as shown by chemical analysis, tend to confirm this determination. But satisfactory optical tests were not obtained.

Augite is a constant constituent of the andesitic rocks, being almost as abundant as feldspar, and forming, with that mineral, the bulk of the rock. It occurs in two generations, forming numerous phenocrysts, and as granular individuals making up a large proportion of the ground-mass. The augite phenocrysts sometimes attain a large size, and are generally sharply bounded by crystallographic planes in forms which yield characteristic octagonal cross sections; again they are rounded or broken by chemical or mechanical deformation; or they form granular aggregates often mingled with plagioclase grains, the allotriomorphic form of the

individuals showing the crystallization of the two minerals to have been simultaneous. The augite is colorless to pale green or yellowish green and is not appreciably pleochroic. It exhibits characteristic cleavages, has a high refractive index, and strong double refraction. The maximum extinction measured from the chief axis in clinopinacoidal sections was 44 degrees; the average of seven readings was 41 degrees. Twinning is very common according to the augite law, the twinning plane being the orthopinacoid. The twins consist of two individuals, separated generally by an irregular surface, or of many broad and narrow lamellæ irregularly alternating, thinning out or ending abruptly in the middle of the crystal. In one case a twin was observed composed of many lamellæ, in which the twinning plane appeared to be the basal plane. Several intergrowths of augite and hypersthene were observed, the augite always inclosing the hypersthene as a peripheral zone. The two minerals have their chief axes in common, and are separated by an uneven but perfectly distinct line. Inclusions of glass in rounded blebs and magnetite in grains and crystals are common, and needles of apatite were noted. Decomposition of augite to serpentine is not rare in these rocks. The serpentine develops about points in the center or on the periphery of the augite crystal, forming sharply-defined areas from which strings and bands of the serpentine extend into neighboring cleavage cracks. It is a finely-felted or fibrous form of the serpentine, in which, when replacement is complete, no definite remains of the structure of the augite can be detected. One crystal of augite was observed to be partly replaced by calcite. Chlorite is rarely present in scaly aggregates, mingled with serpentine in decomposed areas. It appears to be an exceptional product of augite alteration. The augite of the ground-mass is invariably in the form of small, rounded grains, which are identical in color and optical properties with the augite of the phenocrysts. These grains fill the interstices between the feldspar microlites, which they nearly equal in bulk. The occurrence of augite as inclusions in the feldspar phenocrysts has been described.

Hypersthene is a constituent of one phase of the andesites, but is present in small amount. It forms imperfect phenocrysts of

prismatic habit, showing characteristic prismatic cleavage and transverse basal parting. It is nearly colorless and is weakly but distinctly pleochroic: $\mathfrak{c}$ = pale greenish; $\mathfrak{a} = \mathfrak{b}$ = pale reddish yellow. Its intergrowths with augite have already been noted, hypersthene in all cases being the older mineral. Many of the crystals exhibit a network of cracks, which give a granular appearance to the surface. This condition is accompanied by and seems to precede a decomposition into serpentine. The weak pleochroism of the hypersthene suggests that it is a variety of the mineral with low content of iron, an idea confirmed by the absence of dark borders of separated iron oxide about decomposed crystals, which appears to be a common characteristic of normal hypersthene in andesitic rocks.

Olivine, like hypersthene, is a sparing constituent of certain facies of the andesites, and, so far as observed, the two minerals do not occur in the same rock. While the evidence on this point is, of necessity, only negative, and therefore not conclusive, it suggests that olivine is formed at the expense of the hypersthene, or, *vice versa*, as local conditions may determine. This example confirms the opinion expressed by Zirkel * on this point. Olivine occurs as idiomorphic phenocrysts of characteristic form and properties, commonly much altered to serpentine. As the mineral is fully described under another group of rocks in which it is an important constituent, it will receive here but passing mention.

Magnetite is abundantly present in all facies of the andesite, particularly in those containing the least proportion of glassy base. It is found in porphyritic individuals of varying size, with irregular crystalline form, in crystalline grains as a constituent of the ground-mass, and as inclusions in all the other porphyritic constituents. It is also sparingly formed as a secondary product through the alteration of olivine and augite.

Apatite is a constant constituent of the andesites. It is seen included in feldspar and augite in slender, colorless prisms, with hexagonal cross sections and characteristic optical properties. In certain facies of the rock apatite assumes a different appearance. It forms rather stout prisms with irregular terminations and hexa-

* F. Zirkel Lehrbuch der Petrographie, Leipzig, 1894, II, p. 813.

gonal sections, grayish in color and showing distinct pleochroism in tints of bluish gray and pale yellow, the absorption being $e > o$. Its color seems to be due to the presence of minute rod-like inclusions arranged parallel to the prismatic axis of the crystal. These pleochroic crystals occur alike, included in feldspar and augite, and embedded in the ground-mass.

Glass is a variable constituent of the andesites. Its color varies from colorless, through greenish and yellowish tints, to a deep brown or almost black. The opacity is due to clouds of minute-dust-like particles, which, as they occur likewise in adjacent feldspar crystals, probably consist of submicroscopic individuals of magnetite. They may, however, in part be of globulitic character. Besides forming a constituent of the ground-mass of some facies of the rock, glass is widely distributed in the form of inclusions of porphyritic crystals of feldspar and augite.

Of the secondary minerals whose origin may be clearly traced to the original constituents of the rock, serpentine is the most abundant. In color it is greenish to bright or brownish yellow and is non-pleochroic. In ordinary light it appears structureless, but in polarized light it breaks up into a finely-fibrous felted aggregrate, polarizing in pale bluish tints, or sometimes quite isotropic. The color appears to be due to the presence of ocherous iron oxide, probably separated at the time of the formation of the serpentine from its parent mineral. It is found partially or wholly replacing pyroxene and olivine phenocrysts, in cracks and cavities in feldspar, and replacing portions of ground-mass.

Occasional crystals are seen of a mineral of serpentinous aspect which appears to be allied to iddingsite; it will be fully described in another place, it being more characteristically developed in the basalts.

Chlorite and calcite have been shown to occur very sparingly as alteration products of augite.

Limonite occurs abundantly in one facies of the andesite in grains and shreds throughout the ground-mass, and as the filling or lining of cracks, where it forms mammillated coatings. It is clearly secondary, but its immediate source is not evident, as it permeates all the constituents of the rock. It also occurs widely dissemi-

nated as a coloring matter of the serpentine and other minerals, in all forms of the andesite.

Analcite has been mentioned as forming interesting replacements of feldspar. This has taken place in a brecciated andesite, the fragments of which have been largely cemented by analcite, which has also crystallized in vugs and open cracks as brilliant and perfectly-formed trapezohedrons. Thin sections of the rock show that most of the feldspars are wholly or in part replaced by analcite, the alteration having taken place from either the center of the crystal, leaving at times a narrow peripheral rim of undecomposed feldspar, or more commonly by an irregular invasion of the crystal from various points, in which case isolated cores or shreds of feldspar can still be detected. This change affects both phenocrysts and microlites, and appears to be accompanied by the formation of calcite, presumably from the calcium liberated from the plagioclase. The analcite is water clear and wholly isotropic. It was readily decomposed by acid applied to the surface of the thin section, but did not gelatinize, as analcite is said to do by Rosenbusch. The silica separated as a powder which would not hold the stain of the fuchsine solution applied to it. One of the crystals was found to have a specific gravity of 2.256. Analcite is also found in amygdaloidal cavities in one facies of the rock.

The remaining minerals mentioned as occurring in the andesites, calcite, chalcedony, opal, quartz, and natrolite, all occur as the amygdaloidal fillings of cavities in a single facies of the rock, and will be best described under that head.

The Amygdaloidal Andesite.—We may now proceed to the description of the structural and other microscopic features of the andesitic rocks, not, indeed, dealing with each particular lava flow, but rather characterizing the chief varieties into which they may be classed.

One of the most prominent of these varieties is that which, under the designation of the "amygdaloidal andesite," has been described as the basal member of the volcanic portion of the Lower Berkeleyan. The general macroscopic features of the rock have been already sketched in the description of its field occurrence. It is a dark gray to black, compact rock of amygdaloidal habit, which is readily distinguished from the other lavas of this field.

Under the microscope the thin sections exhibit a hypocrystalline structure with occasional porphyritic crystals. These phenocrysts, of which more than two or three seldom occur in a slide, consist of labradorite feldspar and augite in idiomorphic crystals. The ground-mass is a uniform mixture of feldspar microlites, grains of augite, and interstitial glassy matter in nearly equal proportions, with scattered grains of magnetite. The microlites show more or less perfect flow structure and are tangentially grouped about the vesicles, which are frequently drawn out into long wedge-shaped forms, clearly by differential movements of the viscous magma. The vesicles are generally filled with secondary minerals, thus forming the amygdules, which give the rock its distinctive aspect. These amygdules are of all sizes, from that of a pin head up to six inches in diameter, the average size being less than an inch across. Their shape is infinitely varied. The more regular forms are spherical, ovoid, or disc-shaped, cylindrical, wedge-shaped, or almond-shaped; irregular and fantastic shapes are quite as numerous, especially in the more highly vesicular lavas, where the vesicles have moulded one another in expanding. Most of them, however, are chalcedonic only in their outer part, and are then lined with clear vitreous quartz crystals, leaving a cavity at the center, or are filled in solidly with quartz of the same character; or the quartz at the center may be a sugary aggregate. When hollow and lined with brilliant quartz crystals, the latter are often remarkable in being terminated by the positive rhombohedron alone. The centers are sometimes filled with large crystals of calcite, and that mineral has in some cases formed the first layer in the cavity, followed by chalcedony. When such forms are exposed to the weather, the calcite is quickly dissolved, and leaves the outer surface of the chalcedony covered with sharp-cut moulds of the calcite crystals. Calcite forms the sole filling of some cavities. Natrolite occurs frequently alone, and with calcite, chalcedony, and opal, in these amygdules. It is always finely fibrous in radial aggregates. Under the microscope it is cloudy, owing to its exceedingly fine fibration, gives rather high interference colors, and extinguishes parallel to the fibers, the radial form giving neat interference crosses in parallel polarized light between crossed nicols. It gelatinizes

readily with hydrochloric acid. When associated with them it was formed after calcite and opal, and before chalcedony. It was not seen in the same cavity with analcite, though the two minerals occur in adjacent amygdules. Analcite occurs either alone or crystallized simultaneously with calcite. Its properties have already been described. Opal forms the filling of the veinlets already mentioned as frequently traversing the rock, and is the earliest deposit in some amygdules. It is colorless and slightly doubly refracting, the spherical masses exhibiting a dark interference cross.* A bright green mineral was observed in some amygdules, forming an exceedingly thin external coat. A thin section of one of these showed the outer layer to be of opal stained with a green coloring matter of undeterminable character. Chalcedony is, as above stated, very abundant in the amygdules, and exhibits characteristic optical properties. It was deposited after opal, natrolite, and some calcite, and before quartz and some calcite.

It has been shown that the amygdaloidal facies occurs over a large area, and is characterized throughout by the presence of secondary minerals, of which silica in various forms is far the most abundant. As the rock itself is comparatively unaltered, it could not have furnished the great amount of silica thus present, and it is a matter of interest to seek the extraneous source of supply capable of furnishing that substance in sufficient quantity and uniformly over so large an extent. Such a source is probably to be found in a bed of very acid volcanic tuff which commonly overlies the amygdaloidal rock. Circulating waters would readily dissolve silica from this tuff whose porous structure would facilitate such action, and under slightly different conditions of temperature or pressure they would deposit the mineral in the vesicles of the underlying bed of andesite.

The Grizzly Peak Andesite, Porphyritic Facies.—The next most important variety of andesite is that which we have described in the account of the stratigraphy as the "Grizzly Peak andesite." There are two rather distinct facies of this andesite lava; the lower flows, being holocrystalline and laminated, are referred to as the holocrystalline facies, and the upper flows, being distinguished by

*Rosenbusch Mik. Phys., pp. 122 and 89.

a prevailing porphyritic habit, are referred to as the porphyritic facies. Together they make up the greater part of the basal volcanic member of the Upper Berkeleyan. The porphyritic andesite occurs typically along the upper part of the Frowning Ridge escarpment and particularly on Grizzly Peak, and will be first considered. It is, in the fresh condition, a compact massive rock of black color, with pronounced porphyritic habit, the phenocrysts being usually yellowish feldspars with occasional olivines.

Under the microscope the porphyritic structure is strongly marked, large phenocrysts of feldspar, augite, olivine, and magnetite occurring in a microlitic ground-mass. The phenocrysts exhibit striking evidences of the effect of mechanical strains in their very commonly fractured or fragmentary condition. Corrosion and absorption of the earlier formed crystals by the magma is also evidenced. Nevertheless many of the phenocrysts are in beautifully sharp idiomorphic forms, and most of them are clear and unaltered. The feldspar, judging by the extinction angles, is an acid labradorite or andesine. It offers excellent examples of the inclusion of glass and augite, described on another page. The augite is of a pale green color, sharply bounded and little altered. Olivine is sparingly present in large, well-formed crystals, which are mostly decomposed to a bright yellow serpentine. Magnetite forms well-defined crystals of large size, and apatite of the pleochroic variety is quite abundant.

The ground-mass consists chiefly of feldspar microlites of exceedingly small dimensions, with fewer augite granules, minute crystals of magnetite, and a variable but usually small amount of colorless glass. The microlites show a linear arrangement and are tangentially grouped about the phenocrysts, giving evidence of a fluidal structure, not visible in the mass of the rock. The red color of weathered forms of this facies is due to the setting free of hydrous iron oxide through the serpentinization of pyroxene and olivine. The resulting iron oxide as well as the serpentine penetrates the rock in every direction along cracks and fissures, and ultimately penetrates its whole mass. The feldspars decompose to kaolin in the ordinary manner. Chlorite was not observed among the decomposition products in any of the sections prepared, but in

some hand specimens a bright green mineral, probably a chlorite, was observed in spots and bunches as a stain in the feldspars. Iddingsite, derived from the olivine, is very sparingly present. The rock thus described is an olivine-bearing augite andesite. It is thus classed largely on the basis of its chemical character, analysis showing that it is much less basic than the above mineralogical composition would lead us to expect, and clearly of andesitic composition.

On Grizzly Peak and for about 100 feet below the summit, this facies of the andesite is exceptionally rich in glass in the ground-mass, while not differing greatly in its macroscopic aspect from that just described. In thin sections it shows more abundant phenocrysts. Considerable portions of this glassy rock, however, have been brecciated and extensively altered. The fragments of the breccia have lost their dark color and appear gray or white. This change is due to a process of opalization of the ground-mass. The paste in which the fragments are imbedded is similarly affected.

Examined in thin section, it is found that the porphyritic crystals do not differ from those of the unaltered rock, but the ground-mass, while nearly isotropic, has a totally different appearance from the normal glassy base. It appears to be an impure opal, stained with iron oxide and other foreign matter. The brecciation is but faintly emphasized, the substance of the fragments blending indistinguishably with the cementing paste. To test the nature of the isotropic ground-mass, a portion of the rock was finely pulverized and boiled with caustic potash to extract soluble silica if present. By this means the presence of a large amount of soluble silica was shown, and the opaline character of the ground-mass was established. The substitution of opal for the original ground-mass of the rock must be considered as a result of local solfataric action. No further evidence of such action on an important scale has been observed within the area investigated.

The Grizzly Peak Andesite, Holocrystalline Facies.—This variety of andesite is not so distinctly characterized as the two preceding, exhibiting a greater variation of texture and a tendency to merge by gradations into the porphyritic facies. It is repre-

sented by lavas of considerable volume and extent, but in its most typical occurrence is found immediately beneath the lavas last described on the front of the Frowning Ridge escarpment. It also forms a large part of the Ruin Peak Ridge, on the northeast side of Wildcat Creek. It is generally characterized by a lamellar jointage, which has been described on a previous page. In hand specimens it is a dark gray to reddish brown rock of uneven fracture and rather coarse porphyritic habit. It is locally vesicular or amygdaloidal. In thin section it presents a distinctly holocrystalline porphyritic texture. The porphyritic constituents are feldspar, augite, hypersthene, and magnetite, imbedded in a ground-mass of feldspar microlites, augite granules, and grains of magnetite. The plagioclase feldspar, judging from its extinction angles, is a basic labradorite or bytownite. It abounds in characteristic glass and augite inclusions, and shows little evidence of magmatic corrosion or mechanical fracture. The forms of the crystals are not so well defined as were those of the phenocrysts of the porphyritic facies. Orthoclase feldspar is probably present in occasional phenocrysts. The phenocrysts of augite and hypersthene are imperfectly idiomorphic. Augite is very much the more abundant of the two minerals. The feldspar microlites of the ground-mass are generally twinned and extinguished at angles which indicate that they have the composition of labradorite. They show an imperfect linear grouping suggestive of flow structure, but its expression is hindered by the abundance of the phenocrysts. Yellow ocherous serpentine, and a little calcite and chlorite, are the only secondary minerals present in the typical phases of the rock. The calcite is in some cases confined to distinct veins sometimes half an inch in thickness, in which it is crystallized with more or less quartz.

The flow or klinker breccias which are associated with these andesite lavas are as usual more decomposed and altered than the massive lava. The fragments, being often thoroughly vesicular, appear brightly colored, due to the oxidation of the contained iron. The thin sections of these breccias are much obscured by the abundance of iron oxide disseminated through the rock, but the coarser-textured masses seem to have the structure and general microscopic characters of the holocrystalline variety of andesite

modified by secondary action. Besides the iron oxide, opal permeates the rock, filling cracks and considerable areas between the crystals. The cementing material is quite obscured by these secondary products, but may, in part, be fine volcanic ash. It is in this andesite breccia that analcite was found cementing the fragments and replacing the feldspars as described on a previous page.

The 20-foot lens of pale gray, finely laminated andesite which has been described as occurring between the holocrystalline and porphyritic lavas which make up the Grizzly Peak andesite belt, is allied in character to the variety next to be described, but, on account of its association, may be here referred to. In thin section the rock is seen to have a very fine granular structure, with occasional small phenocrysts of feldspar and augite. The ground-mass is chiefly composed of feldspar microlites and granules, with a slight admixture of augite and magnetite grains and little or no glass. The laminated structure so prominent macroscopically is evidenced in the slide by narrow zones traversing the rock at small intervals, in which the feldspar microlites are parallel, the intervening spaces showing no such grouping. The yellowish tint of the separation planes is seen to be caused by the concentration of a pale yellowish serpentine-like mineral along these zones, which imparts its tint to the feldspar, and thus appears to the eye to be crystalline-granular.

Aphanitic Laminated Andesite.—This designation is applied to certain peculiar lavas which are prominently developed in the Campan basin, particularly on Pie Knob and Fog Bluff. The type is confined to the Campan series, in which they occur among the earlier flows. The rock is of a light gray to reddish color, with a well-defined lamination evidently due to flow. As a rule, it is quite aphanitic, although porphyritic crystals may be occasionally detected. Partings are not uncommonly developed along the planes of lamination, but between these the rock is compact in texture, although it may be locally vesicular. This rock seems to have been affected more largely by processes of alteration than any other rocks in the volcanic series. Large masses are seen seamed and fractured in every direction, and intersected by slickensided surfaces of greater or less extent. Secondary minerals

are very widely disseminated through them; limonite filling cracks and cavities, and in streaks following the planes of lamination; calcite abundant in veins and as the filling of vesicles; chalcedony and rarely analcite as amygdules in the vesicular forms; all these secondary products form prominent features in the macroscopic aspect of the rock. Under the microscope it is seen to be holocrystalline, but very fine grained, porphyritic crystals being very exceptional. When there are such, they are plagioclase and augite in imperfectly-formed crystals. The ground-mass is very feldspathic, containing, besides the feldspar microlites, augite granules, and magnetite in grains and rods. Here also secondary products are abundant and prominent. Limonite is in streaks, spots, and concentrically-banded aggregates. Calcite replaces portions of the original ground-mass, and fills cavities in concentric aggregates, alternating with or surrounding limonite. Serpentine, ocherous from included iron oxide, fills interstices of other constituents, and replaces augite grains. Flow structure is well marked by parallelism of the feldspars and by their tangential grouping about phenocrysts and vesicles.

The somewhat arbitrary division of the andesitic rocks into the four facies above named and described, is justified on grounds of convenience and simplicity. It is done, however, in full recognition of the fact that in this, as in every natural group of volcanic rocks, there exists a more or less uniform series of forms, merging one into another by insensible gradations. The frequent occurrence of forms which can not be assigned with certainty to any of our types is sufficient proof of the artificial character of our grouping, which, notwithstanding, has its usefulness for purposes of description. It is altogether probable that a more extended study of the volcanic series over a wider area would not only increase the number of varieties in the andesite group, but would also reveal intermediate forms which would unite the andesites to the basaltic group by a graded series of characters. The intimate field relations of these two groups are such as to confirm the suggestion that, though now regarded as specifically distinct, they are essentially the different facies of the development of a single magma.

Chemical Characters.—The chemical investigation of the andesite group, while not so complete as would be desirable, is yet sufficiently extensive to bring out some interesting points of correspondence and gradation in character between its members, and to establish a good basis on which the group may be differentiated from the associated groups of basaltic rocks. Complete analyses of the four principal types of the andesite and two silica determinations were made and are exhibited in the accompanying table. Comparing these analyses it will be seen that the range of silica is not much above four per cent. It is noticeable also that of the other components the alumina is uniformly high and the iron oxide correspondingly low; the alkalies show but little variation in the first three analyses, but are notably small in VI while the lime is exceptionally high. This analysis shows the Pie Knob rock to be an exceptional type, and its classification with the andesites is recognized as questionable. The specific gravity appears to increase in proportion as the glassy constituent of the rock decreases. The composition of the first three confirms their classification, already made on mineralogical and structural grounds, as pyroxene andesites.

Analyses of Andesites.

	I.	II.	III.	IV.	V.	VI.
SiO_2	59.75	59.74	56.81	57.58	60.79	56.47
TiO_2	trace	trace	trace	.....	.....	.....
Al_2O_3	19.08	19.94	18.36	.....	.....	22.55
Fe_2O_3	.....	1.81	2.48	.....	.....	.95
FeO	2.91	5.41	3.94	.....	.....	1.97
MnO	trace	trace	trace	.....	.....	.....
CaO	6.15	3.74	6.43	.....	.....	10.89
MgO	4.72	1.18	4.75	.....	.....	4.48
Na_2O	4.31	4.65	4.18	.....	.....	.88
K_2O	.92	1.02	1.36	.....	.....	.52
P_2O_5	.15	.35	.25	.....	.....	.....
H_2O	2.64	2.09	1.17	.....	.....	1.03
Total	100.63	99.93	99.73			99.74
Sp. g.	2.62	2.64	2.74	2.66		

I. Amygdaloidal andesite, overlying Orindan formation, Frowning Ridge escarpment. Analyst, Palache.

II. Grizzly Peak andesite, porphyritic facies, southeast of Grizzly Peak. Analyst, Palache.

III. Grizzly Peak andesite, holocrystalline facies, head of Telegraph Cañon. Analyst, Palache.

IV. Summit of Grizzly Peak. Analyst, Palache.

V. Aphanitic laminated andesite, Pie Knob. Analyst, Palache.

VI. Aphanitic laminated andesite, Pie Knob. Analyst, Dickerman.

In the rock whose composition is given in VI, there is about 6.12 per cent of free ferric oxide which as limonite occupies largely the open spaces in the rock, and probably has a source foreign to the rock itself. In the analyses given, this 6.12 per cent ferric oxide has been deducted and due correction made. The rock analyzed is otherwise fresh.

THE BASALTS.

The basaltic lavas are scarcely subordinate to the andesitic in this field. They occur in both Upper and Lower Berkeleyan and in the Campan as important contributions to the accumulations which make up those series. They are found also to a small extent in dyke form. Although they occur, as the andesites do, at many different horizons, and have in the aggregate about the same volume and lateral extent, they are much more uniform in character and exhibit but slight variations in structure and mineralogical composition.

Constituent Minerals.—Mineralogically the basalts consist essentially of plagioclase augite and olivine, with accessory apatite and magnetite. Glassy matter is present in some lavas. Serpentine and iddingsite are the most important secondary products.

The feldspar is in two generations. The porphyritic crystals are sometimes sharply idiomorphic, more generally with indistinct and irregular outline or rounded and embayed by magmatic corrosion. Twins formed on the albite plan are numerous, and Carlsbad and pericline twins are infrequently seen. Extinction angles measured on albite twins which extinguished symmetrically, were as large as 36½ degrees, indicating that the feldspar has the composition of bytownite or anorthite. Zonal forms are common, but less so than in the feldspars of the andesites. The smaller phenocrysts of feldspar are usually quite free from inclusions; the larger ones, which

sometimes attain a size of one half an inch in greatest dimension, are characterized by abundant inclusions of augite, magnetite, glass, and serpentine. These have the same mode of arrangement and the same net-like aspect as was described in the case of the andesites, but here even more abundant than as there described.

The feldspars frequently exhibit irregular cracks, which, as well as the cleavage cracks, are filled with pale yellow serpentine. Alteration seems scarcely to have begun in this mineral, which seems to be the most stable constituent, appearing fresh and glassy in the most rotten specimens of the rock. The feldspars of the ground-mass are both microlitic and granular in habit, more commonly the former. They are, apparently, quite basic in composition, their extinction angles indicating labradorite. Twins are the rule in even the minutest microlites. The microlites sink to almost sub-microscopic dimensions, and on the other hand by increase of size, merge with the porphyritic crystals.

Augite, like feldspar, is in two generations. Phenocrysts of this mineral are almost universally present and generally exhibit sharp idiomorphic boundaries with characteristic form and cleavage. The mineral is colorless to pale fawn color, non-pleochroic, with extinction angle $c \wedge c$ as large as forty degrees. Twins of normal structure are common, and zoned crystals were observed, which gave undulatory extinction. In certain very local forms augite was observed forming ophitic intergrowths with feldspar, the irregular angular areas of augite between the feldspar laths having the same optical orientation over considerable spaces. As a constituent of the ground-mass augite is invariably in small rounded granules, filling interstices between the feldspar individuals, and, apparently, the last product of crystallization of the magma. Alteration of augite appears to be usually to a yellowish serpentine, rarely to chlorite, and has taken place extensively especially in the augite grains of the inclusions and the ground-mass. The calcite observed in the slides is probably due to lime set free from the augite by this decomposition.

Olivine is abundant in most specimens of basalt, and is probably present in all, though not always observed. It is always in porphyritic crystals sometimes of large size and of characteristic

idiomorphic form. These crystals are much rounded and embayed by magmatic corrosion, and fractured by mechanical strains. Its relations to the other porphyritic constituents show it to be the oldest secretion from the magma. The olivine is colorless and non-pleochroic, with high relief, and strong double refraction. Imperfect cleavage is indicated parallel to the pinacoids, the parting parallel to the base being the most pronounced. The alteration of olivine to serpentine may be studied in all stages of development. It usually takes place along the nearly rectangular cleavage cracks, along irregular curved cracks, generally present in the crystals, or from the periphery of the crystal alone. The serpentine is for the most part structureless, rarely showing a fibrous character, the fibers at right angles to the surface of decomposition. As alteration extends away from the cracks, the olivine substance is generally divided up into isolated grains or "eyes," occupying the center of a serpentine meshwork, and the ultimate product is a serpentine pseudomorph, characterized by this mesh structure. An exceptional mode of serpentinization was observed in one large crystal of olivine. Alteration had begun at very numerous points within the crystal and developed radially from them. No definite arrangements of these points could be detected, though the effect was that of an imperfect rectangular system. The round spots of serpentine are connected by a system of extremely fine curving cracks, each filled with serpentine; and in some parts several adjacent spots have coalesced, forming a band of a secondary mineral. The aspect of the crystal thus affected was very similar to that of the feldspar phenocrysts, with net-like arrangement of augite or serpentine inclusions described elsewhere. Olivine also appears to alter to a laminated yellowish mineral, with characters which ally it to iddingsite.

Magnetite is invariably present in the basalts as large aggregate grains and in small sharply-bounded crystals, and elongated, rod-like individuals. In one phase of the rock the sharp octahedral crystals are in part scattered singly through the ground-mass, in part grouped in beautiful reticulated aggregates, the bars of the network formed by octahedrons placed point to point in parallel position and branching at definite angles. Zones of grayish sub-

stance like leucoxene surrounding many magnetite grains indicate that a portion, at least, of that mineral is titaniferous.

Apatite is always present as inclusions in the other constituents in the form of elongated colorless prisms with characteristic optical properties.

The properties of the serpentine, which is so abundantly developed in the basalts, are identical in all respects with those already described for the serpentine of the andesites.

The secondary mineral which has been noticed in both basalt and olivine-bearing andesite, is believed to be iddingsite. It is quite abundant in forms of the basalt which exhibit the most alteration, but in fresher rocks it was seen in process of development from olivine. Macroscopically it is not very prominent, but may sometimes be seen as a bronzy or yellowish mineral with good cleavage. In thin sections it has a pale green to greenish or brownish yellow color, and either the characteristic hexagonal outline of olivine or a sharply rectangular form also seen in olivine crystals in the same slides. Its distinguishing features are a very distinctly laminated or fibrous structure, the fibers parallel to the prismatic axis of the crystal; distinct pleochroism in shades of greenish yellow, the absorption greatest in the direction of the fibration; straight extinction; and strong double refraction, the mottled polarization colors showing bright green and crimson tints. An imperfect parting transverse to the prismatic axis was observed in a few crystals. Crystals showing these characters were seen still retaining unaltered cores of olivine, which is doubtless the parent mineral. No observations were obtained which established the orientation of the optical axis with reference to the cleavage of the mineral. In all observed properties it appears to agree with the mineral described* as iddingsite. If further study should demonstrate its identity with that mineral, it will be of interest as proving that iddingsite may be formed by alteration of olivine, as previously suggested but not confirmed.

* "Geology of Carmelo Bay," Bull. Dept. Geol. Univ. of Cal., Vol. I, No. 1, p. 31, et seq.

Eruptive Rocks of Point Bonita, *Ibid.*, Vol. I, No. 3, p. 90.

Chlorite is sparingly present in some sections of the basalt as an aggregate of pale green color, weak pleochroism and weak double refraction.

Varieties.—The basalts show structural variations, depending chiefly on the degree of development of crystallization and the corresponding coarseness of grain of the rock. Such variations are local in character, and the same flow may exhibit many of them within a very small area.

The most typical form of the basalt, characteristic of the flows reposing on the Siestan formation, is a very fresh-looking dark iron-gray rock, compact and massive, with a fracture varying from even to splintery and uneven. It is distinctly porphyritic, crystals of glassy feldspar, with striated faces, and yellow grains of olivine, the latter sometimes the more abundant and conspicuous, being readily distinguishable with the unaided eye. Pyroxene in well-cleaved plates is also sometimes visible. In thin sections this rock presents the features of a typical doleritic basalt. Phenocrysts of feldspar, augite, and olivine are imbedded in a granular or microlitic ground-mass consisting of feldspar, augite, and magnetite. In rare cases, a typical ophitic structure prevails, the lath-shaped feldspars forming an interlacing network filled in with large allotriomorphic individuals of augite. The ground-mass often exhibits the effects of differential movements of the rock previous to consolidation in the parallelism of the microlites or their tangential grouping about the phenocrysts.

Scarcely less common than this form is an almost aphanitic facies found in portions of flows and the edges of the dykes. It is deep iron black to reddish black in color, with even to subconchoidal fracture, and has a characteristic basaltic aspect. The texture is compact and is either perfectly aphanitic or uniformly and finely crystalline, with occasional crystals of porphyritic dimensions. In thin section these fine-grained basalts show a more or less uniform admixture of lath-shaped feldspars, grains of augite and magnetite, and small idiomorphic crystals of olivine, with generally some glassy matter in the interstices. Flow lamination is more marked in the fine-grained forms of the porphyritic facies, and is often macroscopically visible in an irregular and imperfect lamellar parting parallel to the plane of bedding.

Vesicular or brecciated varieties of the basalt are rare. In the massive flows of the Upper Berkeleyan occasional white dots are visible, which in thin section are seen to be amygdules filled with opal and natrolite or calcite. In the basalt quarry above Pie Knob, where the basalt is seen resting upon gravel, portions of which it has picked up as it flowed along, were found fragments of highly scoriaceous lava, presenting unaltered the aspect of the vesicular scoria which accompany modern lava flows. But at no other point were forms of this character found, and they are undoubtedly exceptional.

The large dyke which cuts the gravels north of Orinda Hill exhibits an interesting variety of structural features. On the edges of the mass the rock is fine grained to aphanitic in texture, dark gray in color, and distinctly laminated. The structure changes rapidly as the distance from the edge increases, till the rock assumes a distinctly granular aspect, with a rough fracture and reddish gray color. In thin section the coarse-grained rock is seen to possess hypidiomorphic granular structure, the idiomorphic feldspar and olivine being surrounded by allotriomorphic augite, and little or no ground-mass present. Here are found the beautiful reticulated aggregates of magnetite described above. In this, the most coarsely crystalline rock found in the area, was found a structure the nature of which is problematical. At irregular intervals small spherical amygdules of calcite occur. In a section cut through one of these there was seen to be, in addition to the filling of granular calcite, a narrow band of dark semicrystalline material intervening on one side of the space between the calcite and the normal rock substance. Further examination revealed other areas of a similar material not associated with amygdaloidal fillings, but forming dark-colored, sharply-defined oval spots about a quarter of an inch across, in the mass of the rock. These spots are scarcely visible in the hand specimen, but in thin section they stand out prominently from the surrounding coarsely crystallized material. They exhibit thin, lath-shaped feldspars, and augite grains contained in a brownish glass full of minute microlites of feldspar and magnetite. Minute areas of calcite and serpentine replace portions of the ground-mass. None of the constituents of

these spots show any definite position with reference to the boundaries of the area, but the lath-shaped crystals of the surrounding rock are arranged tangentially to the oval space, as might be the case in an ordinary vesicle. In short, these spaces seem to be occupied by portions of the magma in which crystallization was checked suddenly at an early stage of development by a cause which did not affect the mass of the rock. Observations were not sufficiently numerous to show whether the occurrence of amygdules with these areas was accidental or otherwise. Their presence may indicate that the disturbing cause which affected crystallization was of a gaseous nature, but this is not certain. They may possibly be variolitic in nature. Whatever their cause, it must have been of an extremely local character, its influence not extending further than a fraction of an inch.

Chemical Characters.—From the above description it is clear that the rocks of this group form a well-defined and closely-related series with the structural and mineralogical composition of olivine-basalt, and dolerite. The chemical composition, so far as known, is in agreement with these conclusions. But two complete analyses of the basalts have been made, one specimen selected being from the flow above the Siestan formation, the other a characteristic basalt from the Campan. Silica determinations were made, however, of other basalts of the series, and the results are presented in the accompanying table. The percentage of silica in these several specimens is very uniform, the extreme range being little more than 3 per cent. The composition as a whole is that of normal basalt. It is interesting to note the close parallelism between these analyses and those of the andesites already given. For comparison, the average of the first three analyses on page 426 is given in column VI. The differences are such as the mineralogical characters of the rocks would lead us to expect, the more basic feldspars and larger olivine content of the basalt being expressed in the lower percentage of silica, and the marked increase of lime and magnesia. The basalts approach very nearly in composition to the dolerite basalts of Etna as shown by the analysis quoted by Iddings.*

*Origin of Igneous Rocks, Table V, p. 207.

Analyses of Basalts.

	I.	II.	III.	IV.	V.	VI.
SiO_2.....	48.03	50.77	48.10	47.61	47.86	58.76
TiO_2	trace	.28	.....	.....	.....	trace
Al_2O	21.81	19.40	.....	.....	.....	19.40
Fe_2O_3...	2.25	4.43	.....	.....	.....	1.43
Fe O.....	6.04	5.59	.....	.....	.....	4.09
Mn O.....	trace	.....	.....	.....	.....	trace
Ca O.....	9.15	9.81	.....	.....	.....	5.44
Mg O.....	6.11	5.25	.....	.....	.....	3.55
Na_2 O.....	4.58	2.64	.....	.....	.....	4.38
K_2 O.....	.44	.30	.....	.....	.....	1.10
P_2O_5.....	.33	.18	.....	.....	.....	.25
H_2 O.....	2.16	1.30@110° .41 ig.	.....	.....	.....	1.96
Total.....	100.90	100.36	.....	.....	.....	100.37
Sp. g.....	2.82	2.79	2.83	2.88	2.80	2.67

I. First basalt above Siestan formation ¼ ml. S. E. of Grizzly Peak. Analyst, Palache.

II. Basalt Quarry E. of Pie Knob. Analyst, Blasdale.

III. Summit of Bald Peak. Analyst, Palache.

IV. Basalt of Frowning Ridge escarpment beneath Grizzly Peak andesite. Analyst, Palache.

V. Basalt of Frowning Ridge escarpment beneath first rhyolite tuff. Analyst, Palache.

VI. Average of three analyses of andesite I, II, III. See p. 426.

THE PYROCLASTIC ROCKS.

The pyroclastic rocks of our field fall into two general classes, viz., (1) light-colored tuffs and agglomerates of rhyolitic composition generally fairly free from ordinary detrital admixtures, and (2) darker-colored tuffs, generally decomposed and associated with or admixed with detrital material. The latter tuffs are basic in the sense that they contain no quartz fragments, but it is not clear in most cases whether they should be ascribed to basaltic or to andesitic eruptions. The rhyolitic tuffs are found chiefly in the Lower Berkeleyan and in the Campan basins, while the more basic tuffs occur at more numerous horizons in both Upper and Lower Berkeleyan and in the Campan. A few words of description are here given of these two classes of tuffs to supplement what was said of them in speaking of their field occurrence.

Rhyolitic Tuffs and Agglomerates.—In the conglomerates and tuffs which constitute the third stratigraphic member of the Lower Berkeleyan, the most important beds on the Frowning Ridge escarpment are whitish tuffs of rhyolitic material. They are more or less distinctly stratified, and weather with rough and pitted surfaces, owing to the heterogeneity of the material. The acid character of the rock may be recognized in hand specimens from the numerous fragments of quartz which appear in it, this mineral, together with feldspar, being large enough for easy identification.

Under the microscope it is clearly seen to be fragmental, the larger component grains being angular or rounded fragments of quartz and feldspar, and occasional rock fragments mostly of a basic character. These are imbedded in a cement of varying composition; glass is usually more or less abundant in shreds and wisps of white or yellowish color; kaolin or a cloudy kaolin-like substance is common, and there is always a certain amount of chalcedony, in some cases so abundant as to replace all the other constituents. Grains of magnetite, hydrous iron oxide, and ocherous serpentine occur irregularly in the interstices, together with undeterminable opaque matter. Both orthoclase and plagioclase feldspars are present in fresh and water-clear crystal fragments; these and the quartzes are frequently rounded and embayed as if by magmatic corrosion, a process which could only have taken place before they were ejected and deposited in the present rock. Such rock fragments as were determinable were of the andesitic character. The chalcedony forms characteristic radial aggregates showing the black extinction cross in parallel polarized light. It occasionally forms compact veins and bunches of greenish color flinty aspect.

A thick lens of very similar rhyolite tuff occurs at a very different horizon in the Campan series in the tuff belt to the northwest of the basalt quarry, and the description just given would apply to it as well as to that of the Lower Berkeleyan.

The tuffs and agglomerates which form the highest member of the Campan series differ from the tuffs just described chiefly in the coarser character of the fragments of which they are composed. In addition to the fragments of quartz and feldspar there are

angular fragments of rock several inches in diameter imbedded in a fine paste. This ground-mass, while of the same general character as that of the rocks described, is more heterogeneous, and the finely comminuted rock and crystal fragments are more sharply angular. It, moreover, presents no evidence of lamination due to sedimentary deposition, as do the lower rhyolite tuffs. Mineralogically, however, it is much the same, exhibiting glass and kaolin with more or less chalcedony, in which are imbedded crystal fragments of quartz, orthoclase, and plagioclase, and fragments of rocks, both acid and basic, the former, of course, greatly preponderating. The larger fragments of the agglomerate which have been alluded to as weathering out prominently on the surface appear to fall into two classes.

The greater number are hard silicious porphyries, white, gray, or green in color, with compact texture and even fracture. Examined in thin section they are seen to be typical microgranites; abundant phenocrysts of quartz, orthoclase, and plagioclase, more or less idiomorphic, but much rounded and embayed by corrosion of the magma, and occasional crystals of brown hornblende and biotite; a ground-mass of microgranular quartz and feldspar, sometimes showing beautiful granophyric intergrowths, and inclusions in the phenocrysts of sharply idiomorphic crystals of magnetite, apatite, and zircon, and of gas and liquid inclusions in the form of negative crystals. The minerals constituting these fragments are identical with those found as more or less broken crystals in the finer portions of the tuffs. There can scarcely be a doubt that they represent in massive form the magma from which the tuffs are derived. The other class of fragments embraces rocks of fine-grained porphyritic texture, green to greenish gray in color, the weathered surface of which is black and pitted by the removal of needle-shaped phenocrysts. In thin section it has the appearance of an altered quartz-andesite. Lath-shaped phenocrysts of plagioclase, occasional corroded crystals of quartz, which may possibly be inclusions, and lath-shaped crystals of fibrous hornblende, are imbedded in a microlitic base of feldspar, magnetite, and glass, colored light green by disseminated particles of uralite and chlorite. This rock is unlike any forms of andesite found in the

volcanic series, in the presence of both quartz and hornblende. The latter, which is uralitic, is probably secondary, and may be derived from augite, but as this process has not been observed in any of the earlier volcanic rocks, even in fragments included in this same tuff, its presence appears to indicate a different origin for the containing rocks.

A specimen of the finer-grained portion of the tuff was found to contain 68.8 per cent of silica. This indicates that the composition of the tuffs as a whole agrees with that of the acid inclusions (microgranite) described above.

The Basic Tuffs.—Owing to their decomposed and altered character, but little results from a microscopic examination of the more basic and dark-colored tuffs. In general it may be said that the volcanic fragments, in so far as they have been examined, appear to be andesitic, some glassy, and others holocrystalline. In the fresher specimens, such as are naturally selected for examination, such andesitic fragments, together with crystals and crystal fragments of plagioclase and augite, are imbedded in a very fine-grained matrix, which is commonly so obscured by the products of oxidation that little can be made of it. When this oxidation is advanced, the tuff may be of a red color, and, in the finer-grained varieties, it is then difficult to distinguish it from the lateritic surfaces of the lavas, or the ancient muds arising from the wash of such laterite.

THE SEQUENCE OF LAVAS.

The volcanic rocks of the Upper and Lower Berkeleyan and Campan series comprise both lava flows and pyroclastic formations. Of these pyroclastic formations the rhyolitic tuffs and agglomerates stand out prominently in contrast to the more basic rocks with which they are intercalated. There are, moreover, no rhyolite lavas in our field with which they may be correlated. The more basic tuffs, on the other hand, seem to be referable to the andesitic and basaltic lavas, with which they are associated, except for certain thin tuff beds low down in the Orindan formation on San Pablo Creek, and similar tuffs in the Siestan formation, for which we have no known corresponding lavas. If we omit these basic

tuffs and make a complete list of the andesite and basalt lavas and rhyolite tuffs in the order of their occurrence, from the amygdaloidal andesite reposing upon the Orindan gravels to the rhyolite agglomerate at the summit of the Campan, we discover a very remarkable periodicity in the sequence.

List of Lavas and Rhyolite Tuffs in the Berkeleyan and Campan Series in Ascending Order of Occurrence, Showing Periodicity of Sequence.

I.	Andesite, amygdaloidal. Basalt, thin flow in tuffs not separately mapped. Rhyolite tuff.	Lower Berkeleyan.
II.	Andesite, outcropping only on San Pablo escarpment. Basalt, thick flows. Rhyolite tuff, thin.	
	(Deformation and erosion.)	
III.	Andesite, Grizzly Peak holocrystalline variety. Basalt, subordinate flow not separately mapped. Rhyolite tuff, thin, superposition on basalt not certain.	Upper Berkeleyan.
IV.	Andesite, Grizzly Peak porphyritic variety. (Siestan lake beds.) Basalts, several flows. ? formations removed by erosion.	
	(Deformation and erosion.)	
V.	Andesite, several flows, with intervening lake beds. Basalt, andesitic. Rhyolite tuff, thick, with other tuffs. Basalt, heavy flows. Rhyolite agglomerate and tuff, summit of Campan.	Campan.
	(Higher beds removed by erosion.)	

The tabulation clearly shows that in the entire succession there is a regularly-recurring sequence in the character of the erupted rocks. There are at least five such recurrences, or periods, and possibly six, if we separate period V into two parts. In four of the five periods the sequence is andesite, basalt, rhyolite. In period IV the rhyolite member is lacking, but may have once

existed, since all formations above the basalt in this period have been removed by erosion in the sections with which we are here concerned. In connection with this apparent defect in period IV it is worthy of note that to the north of Berkeley a sheet of soda rhyolite occurs, which has been described by the junior author of this paper.* This North Berkeley rhyolite is less than half a mile from the northwest corner of the area represented on the accompanying geological map. It is known to be pre-Campan in age, and it is, therefore, entirely possible that it stratigraphically occupies the vacant place in period IV. In period V there is included a fivefold sequence. The first three members conform to the normal sequence of the first three periods. The remaining two members might be regarded as the upper two-thirds of a sixth period.

This remarkable periodicity may possibly be accidental. If a larger field were under consideration it might, perhaps, be found that rhyolite sometimes succeeded andesite instead of always following basalt as it does in these five periods, or that andesite occasionally succeeded basalt instead of preceding it. If any general inference were to be based upon this sequence, that inference would be greatly weakened by these possibilities of accident and of error due to the limitations of the field of observation. The sequence is, however, not so employed. It is regarded merely as contributary data to the general question as to whether there is or is not any normal or natural succession of volcanic lavas. This general question has been before petrologists ever since the publication of Richthofen's classic memoir on a "Natural System of Volcanic Rocks,"† and data have been gradually accumulated upon which an answer to the question will be eventually based. The sequence in the Berkeley Hills is, therefore, but a contributary fact to the many which must be considered before a reliable scientific induction can be drawn. Whether it is an expression of a general law of succession of volcanic rocks or is due to local and special causes will depend on the extent to which it harmonizes with sequences worked out in numerous other localities. The

*This Bull., Vol. I, No. 2.

†Mem. Calif. Acad. Sci., Vol. I, p. 36.

sequence at present known, as worked out for example by Brögger* in the Christiania region, by Iddings† in the Yellowstone Park, by Geikie‡ for Great Britain, and more recently by Spurr§ in the Great Basin, are but partially harmonious, and it is evident that many more observations will be necessary in favorable localities, where the fortuitous or accidental sequence can be discriminated from the normal succession, before an acceptable general law, if there be any such law, can be formulated. The most satisfactory working hypothesis that has been advanced up to the present time is that announced by Iddings,‖ viz., that "the general succession is from a rock of average composition through less silicious and more silicious ones to rocks extremely low in silica and others extremely high in silica, that is, the series commences with a mean and ends with extremes."

Now the various periods of our local succession in the Berkeley Hills are clearly in harmony with this hypothesis, and to that extent support it. To the extent that they are harmonious, moreover, we have some measure of probability that the local sequence is an expression of the normal or general succession of volcanic rocks. It is to be noted, however, that in each of the periods of our sequence, there is an *immediate* passage from the andesite, or rock of intermediate composition, to the basalt, the most basic, without transitions, and similarly an immediate change from basalt to rhyolite. Moreover, the change is always from andesite to basalt and then to rhyolite. In this respect the succession is more definite and more clear cut than is implied in Idding's hypothesis. Further, the periodicity or recurrence of the ternary sequence is more remarkable than the mere harmony of the periods with that hypothesis; and the periodicity minimizes the possibility that the harmony might be a mere coincidence.

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*Q. J. G. S., Vol. L, pp. 15–38.

†The Origin of Igneous Rocks, Bull. Phil. Soc. Wash., Vol. 12, p. 144.

‡Q. J. G. S., Vol. XLVIII, 1892.

§Jour. Geol., Vol. VIII, p. 621, 1900.

‖Loc. cit.

HISTORICAL SUMMARY.

The oldest rocks with which we are in this limited field concerned are those of the Franciscan series. These rocks are known to repose, in neighboring portions of the Coast Ranges, upon the worn surface of a granite, which is believed, for reasons which can not be entered upon here, to be probably of the same age as the post-Jurassic granites of the Sierra Nevada. This implies a post-Jurassic age for the series. The paleontological evidence as to the age of the Franciscan is rather scant, but its fossil foraminifera, molluscs and plants have been independently interpreted by different experts to indicate a place in the geological scale not older than the Lower Cretaceous. Before the recognition of the Franciscan as a distinct series of rocks, the Knoxville had been regarded as the local base of the Cretaceous in California. But it now seems probable that the Cretaceous will have to be enlarged so as to embrace the Franciscan in its lower part.

These Franciscan rocks, comprising a thick accumulation of sandstones, shales, foraminiferal limestones, radiolarian cherts, and volcanic flows, represent a long period of geological time and indicate numerous and important oscillations of level in the basin in which they were accumulating. They are, moreover, traversed very generally by basic intrusives, and with these intrusives are very frequently found irregular zones of contact metamorphism.

The Franciscan was subjected to orogenic deformation and erosion prior to the subsidence which is represented by the Shasta-Chico series of marine sediments. The strata of this series are in the Strawberry Cañon section not more than one-tenth as thick as they are in the northern part of the state, but the general character of the sediments is characteristic of the middle Coast Ranges and is significant of the conditions which prevailed during their accumulation. The Knoxville or basal division of the Shasta-Chico series is prevailingly composed of clay shale or sandy shale, with, in North Berkeley, some limestones, sandstones, and fine pebbly conglomerates. *Aucella* is found equally abundantly in shale, limestone, sandstone, and conglomerate. Belemnites occur in the sandstones, and an ammonite, probably a species of *hoplites*, has been

found in the shales in addition to the *aucellæ*. These beds rest indifferently upon the various formations of the Franciscan, and the latter afford many evidences of disturbance which have not affected the overlying Knoxville. Notwithstanding this fact, however, and the further fact that the Franciscan is made up of characteristic resistant rocks well adapted to yielding pebbles, no fragments of the Franciscan have as yet been found in the Shasta of this region. The radiolarian cherts and glaucophane schists of the Franciscan occur abundantly in the Tertiary conglomerates, and one would naturally expect to find them in the first over-lying unconformable beds. Their absence is in harmony with the generally fine-grained character of the Knoxville beds. These facts clearly indicate that the floor of the basin upon which the Knoxville sediments accumulated was a surface of exceedingly low relief, and that as it subsided beneath sea level there were no insular masses to afford beach material or high-grade streams contributing coarse detritus.

If high land bordered the Knoxville sea, it was so distant from the middle Coast Ranges that the streams contributed practically only suspended matter to the accumulation. It is rare in stratigraphy that such a fine-grained sediment as the Knoxville shales should be so extensively developed immediately above an unconformity, and it is not certain that in the middle Coast Ranges we fully understand the conditions which obtained during the accumulation of these strata. In the southern Coast Ranges conglomerates, with numerous pebbles of characteristic Franciscan rocks, occur, according to Fairbanks,* at the base of the Knoxville.

Above the Knoxville and intervening between it and rocks referred to the Chico, is a stratum of rather coarse pebble conglomerate. This conglomerate barely comes within the limits of our map at the head of Dwight Way, but is traceable for many miles along the front of the range to the southeast, in which direction the stratum increases in volume very noticeably. This formation is certainly significant of a very radical change in the conditions of deposition from those which prevailed in the immediately preceding epoch. We may safely infer the deformation of the region to such an extent as to determine a much higher grade for streams

*Jour. Geol., Sept.-Oct., 1898.

discharging into the existing sea, and at the same time a shoaling of the sea, inasmuch as conglomerates can only accumulate in water of very limited depth. Conglomerates are very commonly formed in broad sheets by the action of a sea encroaching upon a land area, the waves working over the fragments detached from the surface over which the sea is transgressing. This, however, can not be the explanation in the case of the conglomerates with which we are here concerned; for, although the conglomerate occurs characteristically at this horizon* in the Coast Ranges, in extensive strata, yet the action of the sea upon the soft Knoxville shales could produce no such polygenous conglomerate as the one in question. The source of the conglomerates was, therefore, clearly beyond the limits occupied by the underlying shales. But the shales themselves were also derived from beyond these limits, and the change in the character of the materials supplied by the streams could only have been due to a sharp orogenic deformation which strongly accentuated the erosive and transporting power of the streams.

This acute movement was followed by a long-continued, steady, and gentle subsidence of the sea bottom; for, resting upon these shallow-water conglomerates, is a great volume of sandstones with quite subordinate intercalations of shale. These comprise the Chico division of the Cretaceous. The sandstones are for the most part heavily bedded, indicating uniform conditions of deposition, and they are uniformly of medium fine grain. The entire record of Chico sedimentation is not revealed in our field, since the section of these rocks terminates at a surface of erosion. Nor is the attitude of the beds sufficiently exposed to indicate the degree of deformation to which the Chico had been subjected prior to this erosion. In the emergence into the zone of this erosion the region was very probably deformed, but this deformation does not seem to have been acute, since the strike of the beds is in general accord with the unconformably overlying strata.

Reposing upon the erosion surface are beds of the Monterey Miocene, and it is from this fact chiefly that we know that it is an erosion surface; for, as has been already stated, rocks of Eocene

* Cf. Diller and Stanton, Bull., G. S. A., Vol. 5, pp. 435–464.

age, which are abundantly represented in neighboring portions of the Coast Ranges, are here lacking. From this fact we may infer one of two things, either the region was uplifted at the close of the Chico, and this portion of it remained above sea level throughout Eocene time when the Martinez and Tejon were being deposited to a considerable thickness but a few miles away, or it was once covered by Eocene sediments, and these have since been removed in consequence of a post-Eocene uplift, together with some of the underlying Chico. The latter view of the case is the more probable, in view of the proximity of Eocene sediments free from basal conglomerates, but it does not exclude the possibility of an earlier unconformity between the Chico and the Eocene.

The Monterey strata, reposing upon this worn surface of Chico rocks, has a thickness of about 1,000 feet. The transgression of the sea, which permitted of this accumulation, must have been from the east toward the west; for, just to the east of the Berkeley Hills, in Contra Costa County, this particular formation of the Monterey series, characterized by cherts and shales, occurs resting upon still lower sandstones of Monterey age. It is here, again, difficult to understand how, under the normal conditions of transgression, such a formation, composed of cherts and very fine shales, with a minimum of terrigenous material in its composition, could be the local base of the series, unless the region undergoing subsidence were extremely flat, so that a slight depression should submerge extensive areas of the land. This consideration, coupled with the fact, above adduced, that the surface upon which the cherts and shales repose is an erosion surface, points unmistakably to the conclusion that prior to the Monterey subsidence a very thorough peneplanation of this portion of the region had been effected.

The historical significance of the rhythm of sedimentation which so strongly characterizes the Monterey cherts and shales is not clear. Attention has been called elsewhere to a similar rhythm in the radiolarian cherts of the Franciscan; and it might be supposed that a comparison of the two formations, so similar in their composition and in their peculiarities of stratification, would lead to the discovery of some working hypothesis explanatory of the remarkable alternation of conditions which seems to have con-

trolled the accumulation of such rocks. It must be confessed, however, that no very satisfactory hypothesis has yet been formulated. Of course, various extreme possibilities occur to the mind, but we have little or no check upon them. For example, the rhythm might be due to an annual rotation of conditions. This would mean that each pair of layers in the series, one of chert and one of shale, is the result of one year's accumulation. The average thickness of such pairs may be placed at three inches. This would mean that the entire 1,000 feet had accumulated in 4,000 years. This estimate shocks our current conceptions of the rate of accumulation of deposits which are chiefly non-detrital. It involves moreover a startling rate of abstraction of silica from sea water, whether the abstraction be effected by organic agencies or by direct chemical precipitation. If we assume that this particular basin in which the Coast Range bituminous shales were deposited had an area of 1,000x500 miles, the annual deposit would amount to about 100,000 mile-feet of silica in the form in which we now find it, which would be about 200 times, by rough estimate, the total amount of silica contributed annually to the ocean by all the rivers of the world. We have been unable to find figures for the proportion of silica contained in sea water, but the rate of abstraction in this limited area is so much in excess of the supply to the entire ocean that the possibility of the rhythm being due to annual rotation of conditions seems to find little support in the computation. Another possibility is that there may have been some rhythm in the swarming of silica-secreting organisms in the sea water. This, however, in the present state of our knowledge is pure conjecture and can not be regarded as a scientific hypothesis till we have some information which would support it.

Still another possibility is that there may have been some rhythmical supply of silica from purely inorganic sources, such as submarine solfataric springs. The only fact that can be adduced in favor of this possibility is that in the lower part of the Monterey series in Southern California there is a great thickness of volcanic ashes, and that in some other portions of the series volcanic material forms a moderate but distinctly recognizable constituent in the bituminous shales. This, however, contributes

nothing to the probability of *rhythmical* supply of silica from vents connected with this volcanic activity.

It must be admitted, therefore, that we have not at present any reasonable working hypothesis explanatory of the rhythm of sedimentation of these remarkable strata. It may, however, be pointed out that the rhythm referred to is rather local in its development, since we have much greater volumes of the bituminous shales in other parts of the Coast Ranges in which such peculiar bedding is not apparent. The local development of the rhythmical sedimentation appears to be connected with the proximity of this portion of the basin to the land, and to be due to the rhythmical interruption of a continuous deposition of silica by influxes of fine terrigenous silts. If this be a fact, then the explanation of the rhythm in sedimentation must be sought for in the variation of the conditions on the surface of the land, whereby periods of discharge of fine sediments into the sea alternated with periods of little or no discharge. Under such conditions the accumulation of silica, in the outer portions of the sea, removed from the seat of terrigenous deposition, would proceed uninterruptedly, and no rhythm would be apparent in the deposit. This consideration, it may be pointed out, favors the first possible explanation mentioned, viz., an annual rotation of conditions. But the problem is here regarded as an entirely open one, which invites earnest investigation.

In portions of the Coast Ranges only a very few miles distant from the Berkeley Hills to the eastward there are several other formations of the Monterey series aggregating in volume 4,700 feet reposing upon this particular formation of cherts and shales. These higher formations undoubtedly originally covered the region of the Berkeley Hills, but were removed by erosion, after deformation, before the development of the basin in which the Lower Berkeleyan beds were deposited. We have, therefore, at the summit of this formation of cherts and shales an important hiatus in the history of sedimentation of the Coast Ranges. At the close of Monterey time orogenic movements affected this region in common with other portions of the Coast Ranges. The strata were folded, broken, and elevated above sea-level into the zone of erosion.

After the Monterey rocks had been in places partly removed,

together with still lower rocks, a subsidence ensued and the sea once more encroached over the Coast Ranges, and a new cycle of sedimentation was inaugurated for this region. This movement was accompanied by volcanic activity, for the next marine sediments which we encounter in post Monterey time, those designated the San Pablo formation, are in their lower part chiefly sandstones with admixtures of volcanic ash, and in their upper part almost purely pyroclastic sediments, some of which contain fossil shells. These beds of San Pablo age are lacking in the Berkeley Hills, though well developed on the shores of the Bay of San Francisco a few miles to the northward. And it is therefore believed that the San Pablo basin was one lying between insular or peninsular land masses, and that the region of the Berkeley Hills was one of those masses which remained unsubmerged in San Pablo time. Portions of the missing Monterey formation in the Berkeley Hills may, therefore, have been removed during this San Pablo epoch. Following the San Pablo, and in part during the latter part of the epoch, fresh-water basins were developed, probably in consequence of orogenic deformation. In one of these basins accumulated the deposits of the Orindan formation, which lies unconformably upon the rocks of Monterey age. That there was a close connection in time between the San Pablo and the fresh-water deposits of Orindan age is clearly shown from the fact that the pumiceous tuffs of the upper part of the San Pablo are also found in the basal part of the Orindan in the vicinity of Pinole. The Orindan in its full development is not less than 2,400 feet thick, and we seem to have in such an accumulation of fresh-water beds, chiefly lacustrine but probably also in part fluviatile, very clear evidence of depression of the region during their accumulation. That such depression was orogenic or local rather than epeirogenic seems also clear, since a general depression would undoubtedly have admitted the sea, and we find no trace of marine conditions in the basin, except to the southeast, where, to the west of Bollinger Cañon, we find that the sea at the close of the Orindan, had access to the basin for a time, and marine conditions displaced the lacustrine. The marine beds attain a thickness of about 2,000 feet, and their fossil fauna is, in the opinion of Prof. J. C. Merriam,

closely allied to that of the San Pablo formation. These beds constitute the Trampan formation, so named from Las Trampas Creek, along which they are exposed. Their presence here, signifying the local displacement of the fresh water by the sea, is clearly indicative of orogenic deformation of the basin during the progress of its filling up. This marine encroachment did not apparently extend to the Berkeley Hills, for we find no trace of marine sediments between the Orindan formation and the overlying volcanics.

The accumulation of the Orindan and Trampan formations was brought to a close in the region of the present Berkeley Hills by the outburst of volcanic activity; lavas spread out over the floor of the basin; but the lake was re-established, for we find lacustrine deposits between some of the lavas, notably 30 feet of fossiliferous fresh-water limestone intercalated with the basalts of Eureka Peak. Finally, however, this lake was drained, or more probably displaced. The basin was then subjected to deformation, by which the strata were flexed and elevated. The erosion which followed had cut out important channels, when another set of lavas, the Grizzly Peak andesite, occupied these channels and also spread out over the earlier lavas. In the channels we find the lavas of the second epoch, Upper Berkeleyan, are reposing upon the worn upturned strata of the lake beds. The occupation of the drainage channels by these Grizzly Peak andesites re-established lacustrine conditions, and the Siestan lake was the result.

This lake became filled with a varied assortment of sediments to a depth of about 200 feet. Their fine character and general absence of delta material indicate that the lake had a somewhat prolonged existence. The lignitic character of some of the beds, the occurrence of fossil leaves in others and of well-preserved trunks of trees in others, points to abundant vegetation on the shores of the lake. The two well-defined beds of limestone generally free from detrital admixtures, and having a thickness of from 10 to 20 feet, with other thinner beds of less importance, contribute to the idea of long duration for the lake. They also afford a picture of clear waters comparatively free from sediment during their accumulation. They, moreover, indicate a non-organic source for the carbonate of lime of which they are composed.

The occasional thin beds of volcanic tuff found intercalated with the clays and shales in the Siestan basin, tell us of the spasmodic sputtering of a volcano in the region, but too distant or too inactive to pour its lavas into the lake.

Eventually, however, this volcanic energy burst forth in floods of basalt, which destroyed the lake and occupied its basin. Between these flows there were considerable intervals, as is shown by the oxidized surface of the lava and by the presence of tuff beds at the same horizon with thin beds of limestone deposited in a new sheet of water established on the surface of the first flows.

To what extent these lavas piled up over the Siestan basin we can not now tell, for the surface at which they terminate upwards is one of erosion.

The occupation of the Siestan basin by these lavas was followed, after an interval of unknown length, by the deformation by flexure of the entire region, and what remains of the Siestan lake beds and of the overlying lavas occupies the axis of the great synclinal trough. The establishment of this structure was followed by prolonged erosion, whereby the upturned edges of the folded strata were worn down and the corresponding anticlines entirely removed.

Across the northwest end of what then remained of the syncline there was established the Campan basin, probably by a renewed deformation of the region. The earliest rocks to occupy this basin were clays and shales, with lenses of fresh-water limestone, sandstones, and conglomerates. These were followed by alternations of lavas or tuffs and lake beds, the last of the series known to us being a rhyolitic tuff and agglomerate, of which the succeeding erosion has left only a few remnants capping the hill tops.

In the midst of this Campan accumulation the basin was converted by the Cañon fault into a structural trough, which the later lavas and tuffs filled up.

After the Campan basin and trough was filled, it was synclinally folded and variously faulted, the faults apparently belonging to the same system of movements which in part gave rise in later time to the depression now occupied by the valley of the Bay of San Francisco. But before this valley was evolved, the region had

yet to undergo a most extraordinary history. The Merced series on the peninsula of San Francisco only a few miles distant is post-Campan in age. To permit of its accumulation, that portion of the region sank over a mile beneath sea level, and the trough so formed was filled to the brim with marine sediments of late Pliocene, and in their upper part of Pleistocene age. Then this trough was deformed, the floor upon which the Merced was laid down was lifted high above sea level,* the Merced beds were tilted at angles as high as 75 degrees, and were dislocated by a fault having a throw of not less than 7,000 feet.† After this we enter upon the cycle of erosion, vertical oscillations of the coast, and minor faulting, which has resulted in the modern geomorphy of the middle Coast Ranges.

University of California,
December, 1901.

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*Cf. this Bull., Vol. I, No. 4.

†Cf. Sketch of the Geology of San Francisco Peninsula, U. S. G. S., 15th Ann. Rpt.

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